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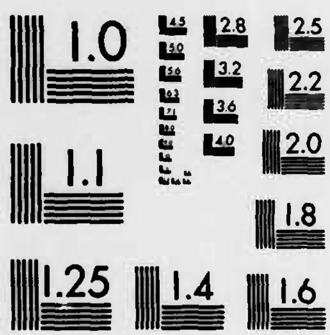

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THESIS

MEASUREMENT OF VELOCITY DISTRIBUTIONS IN TURBULENT JETS USING A LASER DOPPLER VELOCIMETER

by

Mark Donald Wessman

June 1983

Thesis Advisor: W. G. Culbreth

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Measurement of Velocity Distributions in Turbulent Jets Using a Laser Doppler Velocimeter

by

Mark Donald Wessman
Lieutenant Commander, United States Navy
B.S., University of Utah, 1971

Submitted in partial fulfillment of the requirements for the degree of

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June 1983

Author: Mark D. Wessman

Approved by: William Culbreth
Thesis Advisor

Matthew Kelleher
Second Reader

P. J. Marto
Chairman, Department of Mechanical Engineering

J. N. Dyer
Dean of Science and Engineering

ABSTRACT

The theory of operation of Laser Doppler Velocimeters is discussed for both reference beam and differential Doppler modes. Current entrainment models for velocity distributions in vertical axisymmetric turbulent buoyant jets in a quiescent ambient are reviewed. A specific Laser Doppler Velocimeter is used to measure the velocity distribution found in a vertical, axisymmetric turbulent jet discharged into a quiescent ambient and the results are compared to theory.

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TABLE OF SYMBOLS

B	Characteristic jet width (L)
D	Jet discharge diameter (L)
E	Volumetric entrainment rate, dQ/dS (L^2/T)
F	Densimetric Froude number, $U_o/D\{(gD(\rho_a - \rho_o/\rho_o))\}^{1/2}$
F_L	Local densimetric Froude number, $U_m^2/\{gB(\rho_a - \rho_m)/\rho_m\}$
f	Frequency (Hz)
g	Gravitational acceleration (L/T^2)
Q	Volumetric flow rate (L^3/T)
r	Radial jet coordinate (L)
S	Streamwise jet coordinate (L)
U	Streamwise jet velocity (L/T)
v	Velocity of particle (L/T)

GREEK SYMBOLS

α	Entrainment coefficient
θ	Angle of beam crossing, angle between lines of sight in reference beam mode.
ϕ	Angle between velocity vector and fringe pattern normal, angle between velocity vector and the scattering vector.
λ	Laser light wavelength (L)
ρ	Density (M/L^3)

SUBSCRIPTS

a	Ambient condition
d	Doppler shift
m	Evaluated at local jet centerline
o	Evaluated at the centerline of the nozzle exit

ACKNOWLEDGMENT

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I. INTRODUCTION

The study of the characteristics of turbulent jets and plumes has become an item of widespread interest as the concern for the environment has grown. An understanding of how the velocity profile varies throughout the jet is central to the development of knowledge of the behavior of the jet with respect to heat and mass transfer, both subjects of intense interest to the engineer or scientist who must predict the impact of a discharge on the environment. Further, changes in temperature or concentration may someday have significance in non-acoustic antisubmarine warfare applications.

Researchers have used a variety of techniques to study turbulent jets and plumes. Qualitatively, the characteristics may be disclosed through photographic studies involving the injection of tracer dyes. For the purposes of determining the widths of the plumes and their trajectories, this technique is useful, but precise velocity information or numeric data regarding the temperature or concentration profiles within the fluid are not available from this method. Velocity information, as well as temperature can be determined using hot wire anemometry, but this technique requires that a probe be inserted in the flow in order to obtain the measurement. The presence of the probe is intrusive in nature and will invariably alter the flow characteristics of the system. Similar objections arise when the use of rakes of thermocouples, conductivity probes, or any similar device is contemplated. For years, however, no alternative existed and researchers were required to make do, minimizing the effects of the measurement devices if possible.

In 1964 [1] [2], it was noted that laser light in a flow in which particles were present was scattered, and that the scattered light was shifted in frequency by an amount proportional to the velocity of the scattering particles. Subsequent work developed the technique, known as Laser Doppler Velocimetry or Laser Doppler Anemometry, with the result that there is now a reliable, non-invasive method of measuring fluid velocity in a variety of environments.

For the purposes of the present work, a commercial Laser Doppler Velocimeter was obtained. The device was interfaced with a Hewlett-Packard 9826 microcomputer for data acquisition, a tank was constructed and a suitable nozzle was installed for the introduction of a vertical submerged jet of water into an ambient. Here the intent was to gather data on a jet discharging to the quiescent medium of the tank, and to develop the measurement procedures, interfacing programs, and data reduction facilities necessary to analyze the behavior of the jet. The results were compared to those obtained by earlier researchers under similar conditions with the objective of validating the technique and ensuring proper functioning of the system.

Data was collected at a variety of flow rates in quantities sufficient to constitute a valid statistical base. Raw data gathered by the microcomputer in conjunction with the LDV electronics was transmitted via telephone line to a Digital Equipment Corporation VAX 11/780 computer, which was large enough to perform the required manipulations to reduce the data to usable form. Results were expected to be consistent with those obtained by other researchers utilizing other methods.

Specific information to be gathered and compared was:

1. The jet centerline velocity as a function of streamwise coordinate and the velocity of discharge at the nozzle axis.
2. The variation of jet characteristic width with streamwise coordinate.
3. The rate at which the ambient fluid is entrained into the jet, as characterized by the entrainment constant.

Information which was also gathered in order to demonstrate the capabilities of the system included:

1. The mean velocity component normal to the streamwise coordinate.
2. The turbulence intensities in the radial and streamwise directions.

3. The mean Reynolds stress at the point of measurement.

The measurements were made using the LDV to gather data in first the streamwise direction, then, after rotating the plane of the beams, in the direction normal to the streamwise coordinate. No attempt was made to take instantaneous readings in the two directions simultaneously, as this model LDV possesses no capability to do so.

As the data was gathered, the velocity information was monitored on the screen of the microcomputer, which was programmed to provide a display similar to that of a spectrum analyzer. As each sample was received, the data point was plotted, accumulating vertically with an abscissa representative of the velocity. The resulting plot represented the number of "hits" at a particular velocity over the total sampling time. In general, the accumulation of 100 or more points of data provided a distribution which was Gaussian in nature, and which could then be saved on flexible disk for further processing.

The ability to accurately determine mean velocity at selectable points within the jet allowed confirmation of the shape of the velocity profiles within the body of the jet. This is of particular value as most models so far postulated assume a Gaussian profile radially and that the centerline velocity decays inversely with the streamwise coordinate dimension. It was expected that these assumptions would be verified during the course of the investigation.

II. LASER DOPPLER VELOCIMETRY

Laser Doppler velocimetry (also known as Laser Doppler Anemometry), is a relatively new technique for the measurement of velocities in fluids. It is dependent on the wave mechanics of light in the medium of interest, but requires no physical probe to be inserted into the flow, and is, therefore, non-intrusive in nature. The method has been used to measure mixing in chemical reactors, flow through nuclear reactor fuel bundles, chemically reacting flows, and flows in other environments where the geometry or the nature of the fluid to be studied precludes the use of other techniques. It has been used in both gases and liquids.

Drain [3] presents the theory and techniques of Laser Velocimetry on an introductory level and covers the currently used methods and processes in some depth. Only those topics necessary for background or understanding of the methods used in the present work will be discussed here.

A. THE REFERENCE BEAM TECHNIQUE AND THE DOPPLER SHIFT

The Doppler shift is a well known phenomenon which has been widely utilized in acoustics and in radar applications. Because light is a form of electromagnetic radiation, scattered light from particles in a fluid flow is also Doppler shifted by an amount determined by the relative velocities of the source, the particle, and the detector. For a stationary source and detector, the amount of the Doppler shift observed is a function of the half angle of scattering and the component in the direction of scattering of the velocity vector of the particle scattering the light. As the geometry of the system is a known quantity, the velocity of the particle can be obtained directly from the Doppler shift frequency. This is the principle of operation of the reference beam mode in Laser Anemometry.

Because of the speed at which light propagates, the derivation of the Doppler shift must include relativistic effects in order to be rigorous. Applying the equations of special relativity and using the final approximation that the velocity of the particle is very small compared to that of light, the Doppler frequency shift can be shown as:

$$f_d = (2v/\lambda)\cos\phi\sin(\theta/2)$$

where v is the particle velocity, λ is the wavelength of the light, and ϕ is the angle between the direction of scattering and the particle velocity vector, and θ is the angle between the original beam path and the line of sight from the particle to the detector. The scattering direction is defined in Mie scattering theory as the direction of the bisector of the obtuse angle formed by the lines from the source to the particle and the particle to the detector. Figure 1 shows the geometry.

In practice the Doppler shift frequency is very low in comparison to the frequency of the laser light (32 MHz Doppler shift at 10 m/sec for red light such as from a He-Ne laser at a frequency of 4.7 X 10^{14} Hz, a ratio of 7 parts in 10^{8}). Such a low variation in frequency is extremely difficult to detect. Furthermore, the output frequency response of most detectors is far lower than optical frequencies. Accordingly, a technique must be used whereby improved frequency response is obtained and the Doppler shift more readily detected. Mixing Doppler shifted light with light of the original frequency is a technique similar to that used in superheterodyne radio and radar transmitters to move signals to more favorable parts of the electromagnetic spectrum. The light of the original frequency is the reference beam from which the technique takes its name.

When two coherent (i.e., of a fixed phase relationship) signals are mixed, the result is a signal with constituent waves of frequencies corresponding to the sum and the difference of the original frequencies. In optical detector systems, the sum component is at a frequency much too high for the bandpass characteristics of the system to process and is thus filtered out. The difference signal, however, is at a lower frequency which is easily processed, and which corresponds to the Doppler shift frequency.

Physically, the reference beam is generally split off of the illuminating beam before it passes through the fluid. It is redirected to be finally focused on the detector pinhole, mixing with the scattered light from the main beam. It is sometimes necessary to attenuate the reference beam in order to assure similar intensities of the signals at the surface of the detector.

The reference beam technique has been used with success in a variety of applications. However, its applicability is limited by a low signal-to-noise ratio which renders it less useful than the differential Doppler technique. The arrangement of a typical reference beam LDA is found in Figure 2.

B. THE DIFFERENTIAL DOPPLER TECHNIQUE AND THE FRINGE MODEL

If two beams of coherent light, both of equal intensities are crossed in the body of a moving fluid, light scattered from the intersection volume will be shifted by an amount equal to the difference between the Doppler shifts of the light scattered from the individual beams. This shift can be analyzed similarly to the case of the reference beam method, but a simpler model is available to explain the results obtained. This is the fringe model.

The formation of interference fringes has been observed using diffraction gratings, pinholes of specified separation, and many other simple optical devices [4]. These fringes are the result of constructive and destructive interference between the wave fronts of the light where they are coincident. The same result occurs when beams from coherent sources are crossed in space. The maxima of the light intensities resulting from the mixing are the bright planes of the fringe pattern and correspond to the loci of points at which the wavefronts are in phase. If the beams are crossed at angle θ, the spacing of the fringes can be shown to be given by:

$$d = \lambda/2\sin(\theta/2)$$

The fringes are parallel to the bisector of the intersection angle of the beams. If a particle passes through the pattern at velocity v, the scattered light will be modulated in intensity at a frequency given by;

$$f_d = (2v/\lambda)\cos\phi\sin(\theta/2)$$

This is the differential Doppler frequency, and the process is the basis of the differential Doppler method. Here ϕ is the angle of the velocity relative to the normal to the fringe planes. Figure 3 depicts the geometry of the fringe model.

The frequency of light scattered from the intersection volume using the differential Doppler technique is independent of angle. This fact allows collection of the signal at any angle which is advantageous to the purpose at hand. If the detector is positioned in the hemisphere beyond the intersection volume from the laser or beam source, the term "forward-scatter" is used. Conversely, if the detector is on the same side as the source, the term "backscatter" is used. Collection in the forward-scatter mode provides greater signal strength while, if backscatter is used at 180 degrees, the receiving optics can be combined with the transmitting optics. Backscatter, however, is limited by a much lower signal strength.

Light intensity across the beam fronts is not uniform, but varies in a Gaussian manner radially. As a consequence, the volume of intersection of the beams is ellipsoidal in shape and the intensity of the fringes varies across the cross-section of the intersection volume. This results in a lower frequency modulation of the differential Doppler signal which is called the pedestal. The pedestal is unwanted noise and is usually removed by filtering before signal processing begins.

A diagram of a typical differential Doppler arrangement is found in Figure 4.

C. FREQUENCY SHIFTING

As a particle passes through the intersection volume in the differential Doppler mode, the light scattered is modulated at the differential Doppler frequency corresponding to the component of velocity of the particle normal to the fringe planes. For flows in which the direction of travel is always known, sufficient information can be obtained to characterize the flow. In highly turbulent flows where flow reversals are present or in similar cases such as mixing, an ambiguity exists as to the direction of flow. Furthermore, since the signal is generated by the movement of particles with respect to the fringes, a zero velocity results in an absence of signal. Both of these problems are eliminated through the use of frequency shifting.

The technique of frequency shifting consists of altering the frequency of one or both of the crossed beams by a fixed amount. This can be accomplished by the use of mechanical or electro-optical devices, the most common method being the use of the electro-acoustic Bragg Cell.

When frequency shifting is used, the fringes will move with a velocity determined by the frequency shift. Directional ambiguity and loss of signal at zero velocity are now eliminated, and the true velocity of the particles may be determined by subtracting the frequency shift from the measured differential Doppler frequency, and then proceeding with the computations as though no frequency shift had been applied.

The Bragg Cell consists of a block of acousto-optic material on one side of which a piezoelectric transducer is affixed to impart the acoustic excitation to the block. The acoustic waves traveling through the cell diffract the laser light causing the it to be shifted in frequency by an amount equal to the frequency of the acoustic wave. Successive acoustic waves cause the signals to reinforce yielding an improved efficiency in transmission. It has been found that a shift frequency of about 40 MHz can provide 80% efficiency and result in sufficient separation of beam orders to allow for easy blocking and selection. In many currently used systems, the plus first order beam is used at a 40 MHz shift because the wavelength of the acoustic waves is comparable to the diameter of the beams to be shifted.

Either one or two Bragg Cells may be used in frequency shifting applications. Usually if one cell is used, a downmix frequency of 32 to 35 MHz is used to reduce the observed signal in frequency to a range where the frequency response characteristics of the installed instrumentation are better adapted to handle it. In the two Bragg Cell technique one is usually operated at the most efficient frequency for transmission (40 MHz is typical) and the other operated at the amount of shift desired above the reference. The net shift detected is the difference of the two, providing selectable frequency shifting on the order of magnitude of most flow measurement velocities encountered, while maintaining optimum beam power.

D. SIGNAL DETECTION AND PROCESSING

The signal of interest in laser velocimetry is optical in nature and is hence detected by means of optical instrumentation. A photomultiplier tube or photodiode is most often used as the primary detector. Photomultipliers provide inherent amplification features and have good frequency response characteristics up to 10 to 100 MHz. They are most responsive in the blue to green portion of the spectrum but can be obtained with good response in the red to infra-red regions. Photodiodes usually have no inherent amplification attributes, but can be avalanched to provide some multiplication. They are usually most sensitive in the red to infra-red, although adequate sensitivity may be obtained across the visible spectrum.

Signal analysis can be accomplished through a variety of means. The method used is dependent on the type of information required. For low Doppler frequencies, spectrum analyzers can be used to provide frequency information from the signals. Counter-tracker arrangements and autocorrelators can be used to separate the noise from the signal and to yield the frequency information. Any signal processing arrangement must include provision for filters to adjust the bandpass characteristics of the system to maximize the signal-to-noise ratio. Low frequency filters (high pass filters) are used to remove the pedestal while low pass filters are adjusted to eliminate high frequency noise such as that from thermal sources and photomultiplier tube "shot noise".

For the present work, a counter type signal processor was used to provide frequency information for each burst as sampled. The processor used a high speed clock (250 MHz) in conjunction with Schmitt triggers to measure the duration of a burst of a fixed number of cycles. The frequency was then obtained from the number of cycles measured and the time required for the burst. Filtering was provided in the apparatus before the counter tracker.

E. VELOCITY AND FRINGE BIASING

The results obtained by laser anemometry can be biased in two principal ways. The first, velocity biasing, is the biasing of the mean velocity by the disproportionate inclusion of high frequency bursts over low. This occurs primarily at low data rates when the registration of a data point results from the passage of a single particle through the intersection volume. In a flow with uniform particle density, more particles moving at a high flow rate will pass through the measurement volume than will particles moving at low velocities. This is a consequence of a high velocity particle having a higher probability of encountering the intersection volume. If a sufficiently high data rate is present that the data acquisition system samples at uniform intervals at a rate much slower than the data rate, velocity biasing is eliminated and the time average frequency will yield the correct mean velocity. If such a high data rate cannot be maintained, the data must be weighted with the duration of each burst sampled. This will correct for the low probability of sampling a low velocity particle.

The second biasing, fringe biasing, is a result of the parallel nature of the fringes. If a particle passes on a course parallel to the fringes, no signal will be generated. Therefore, even though a significant number of particles having a zero component of velocity in the direction being measured can exist, only particles having a non-zero component will be "seen". The use of frequency shifting causes the fringes themselves to move and eliminates the bias by generating a relative motion between the particles and the fringes.

F. SEEDING OF FLOWS

Many flows of interest to the LDV user do not include enough particulate matter to scatter the light and provide a signal. In those cases, an appropriate seeding particle must be chosen. There are two basic requirements for scattering particles. First, they must follow the flow sufficiently well to adequately represent the dynamics of the system. Second, they must scatter sufficient light to provide a good signal. Consideration must also be given to special conditions such as high temperature or chemical reactivity of the flows in the selection of the seeding particles. The manufacturers of most commercial laser Doppler velocimeters provide guidance in the selection of appropriate particles for use with their apparatus.

III. CIRCULAR BUOYANT JETS

The characteristics and behavior of circular buoyant jets have been the subject of many studies in the past four decades. Most of these studies have involved not only experimental observations but also mathematical model development in an effort to accurately predict plume and jet behavior under a variety of conditions. By far the most widely utilized model is the entrainment model which attempts to predict jet behavior based on integral equations of continuity, momentum, and energy. Other approaches utilized an analysis based on Prandtl's mixing length hypothesis or on turbulence kinetic energy. Schlichting [5] discusses these more traditional approaches.

The entrainment model has been used by numerous authors in their studies, and general agreement on the forms of the equations and constants involved has been reached. Gebhart et al. [6] have provided a comprehensive discussion of the various models and have employed a number of them for comparative calculations. The models predict not only trajectory and velocity behavior in jets but also deal with the temperature and concentration fields found in jets in uniform and stratified ambients, either quiescent or flowing. For the present work only the information which pertains to velocity distribution and jet growth will be considered.

A. GENERAL PROPERTIES OF JETS

The physical extent of a buoyant jet can be divided into three zones. The first, the Zone of Flow Establishment, is that region in which the flow transforms from the characteristics found in the nozzle to those of a free jet. In this region momentum effects predominate and the velocity, temperature, and concentration profiles found in the flow field are typical of the nozzle itself. The flow at the core of the jet is unaffected by the surrounding ambient, and viscous shear effects act at the periphery of the jet to initiate mixing with the surrounding fluid. The Zone of Flow Establishment ends where the turbulent mixing reaches the core of the jet.

The second region is the Zone of Established Flow. Here buoyant effects and momentum effects of the jet are on the same order of magnitude. Velocity profiles (as well as those of temperature and concentration) are similar throughout the region. Interaction with the ambient remains through viscous shear at the boundaries and mixing proceeds throughout the jet. The initial discharge conditions of the jet play a progressively smaller role as the jet grows toward plume-like behavior.

In the final region, the far field, momentum effects of the jet are negligible and the behavior is influenced by buoyancy effects. The jet is free to be convected passively by the ambient. Diffusion acts as the jet loses definition and becomes indistinguishable from the surroundings.

The terms jet and plume refer to submerged discharges which have primarily momentum and buoyant behavior respectively. A pure jet can be considered to be a discharge of fluid of the same density as the ambient injected at some velocity relative to the surrounding fluid. A jet's behavior is determined by its momentum when discharged and it reacts with the ambient only through viscous shear at the boundary. Conversely, a pure plume can be considered to be a discharge of fluid into an ambient of significantly differing density injected at a low enough velocity that momentum effects are negligible. A pure plume may also be created by the injection of energy to the fluid such as through immersion of a hot wire in the ambient. A plume may be either positively buoyant or negatively buoyant. Clearly, real world discharges are rarely either pure jets or pure plumes. In this work the terms jet and plume will be used interchangeably and will be understood to apply to a discharge of a fluid into an ambient which will be considered to be infinite in extent and which is not required to have the same composition or properties as the jet.

Ambients may be described as stratified or unstratified as well as flowing or quiescent. A stratified environment is one which possesses layers of fluid of differing properties within its extent. Situations of interest because of parallels in nature are those involving vertical stratification of water either thermally or with respect to salinity. In the laboratory, the environment stratified with respect to salinity is the easiest to control and is, therefore, the one usually studied. Here, however, the object is to compare LDV measurements with theory. Accordingly, the ambient of interest will be selected as quiescent, unstratified water in the interest of simplicity.

In addition to classification as jets or plumes, discharges may be described by their angle of discharge with respect to the gravity field. A vertical jet is one discharged parallel to the gravity field (in either the same or the opposite sense) and a horizontal jet is one discharged normal to it. Obviously a jet can assume any orientation, and the orientation may change over the flow field if buoyancy is present. For the present work, the vertical jet has been selected to provide for a stable, predictable trajectory in the presence of buoyancy effects.

B. ENTRAINMENT MODEL FOR THE QUIESCENT AMBIENT

Morton et al. [7] were the first to use the entrainment model which supposes that the rate at which fluid is brought into the jet is proportional to the centerline velocity of the jet and to the effective circumferential area of the jet. Mathematically,

$$E \propto 2\pi B U_m$$

Here E represents the volumetric rate of entrainment into the jet, B is some characteristic dimension of the jet yet to be defined, and U_m is the mean centerline velocity of the jet. This rate of entrainment must be equal to the rate of change of volumetric flow within the jet or,

$$dQ/dS = E$$

Here Q is the volumetric flow rate and S is the streamwise coordinate of the jet. The constant of proportionality defining E is called the entrainment constant or entrainment coefficient, α. Utilizing the notation thus defined, the entrainment function becomes

$$E = 2\pi\alpha B U_m$$

The assumptions used in the solution of the equations for differential modeling of the plumes are as follows:

1. The turbulent jet flow is steady.
2. Since the jet flow is fully turbulent, radial molecular diffusion is neglected, compared to radial turbulent transport.
3. Streamwise turbulent transport is negligible when compared with the convective streamwise transport.
4. The variation of the fluid density throughout the flow field is small compared to a chosen reference density. Density variation is significant only in buoyancy terms. (Boussinesq approximation).
5. There is no variation of other fluid properties throughout the flow field.
6. Pressure is hydrostatic throughout the flow field.
7. The jet is axisymmetric. That is, throughout the flow field there is no variation circumferentially of any important parameter.

Most modelers have assumed a Gaussian profile for velocity in the jet. That is, the velocity in the jet cross section will vary as:

$$U = U_m \exp(-r^2/B^2)$$

Here B^2 is twice the variance from the mean centerline velocity of the local velocity across the jet. Using this definition, B can be seen to represent the radial coordinate at which the mean velocity has decayed to 1/e of the mean centerline velocity. B is therefore representative of the nominal half width of the jet and is the quantity used in the entrainment relations. A similar Gaussian profile has been assumed for variations of temperature and concentration to complete the models, but a spreading factor equal to the square of the turbulent Schmidt number is added to the denominator in the exponent. See Gebhart [6] for details.

In the Zone of Established Flow, which is of principal interest here, buoyant forces and momentum effects are both important. The relative importance of these quantities can be represented by the value of the densimetric Froude number, F. It is defined by:

$$F = U_o/\{gD(\rho_a - \rho_o)/\rho_o\}^{1/2}$$

The importance of the initial momentum is given by the discharge velocity U_o and the contribution of the buoyancy force is represented by the density difference. It is a measure of the velocity generated by the buoyant force. Hereafter, the densimetric Froude number will be referred to as simply the Froude number. In some models, the local

Froude number is used. It is defined as:

$$F_L = U_m^2/\{gB(\rho_a - \rho_m)/\rho_m\}$$

Mathematical models using the entrainment function provide prediction of velocity, concentration and temperature profiles, trajectory, and jet width once the entrainment constant is specified. The determination of the entrainment constant has been empirical in nature, with several researchers recommending specific values or forms for correlations. While many of these have been formulated for variable orientation or for flowing ambients, they will not be addressed here; rather those relations germane to quiescent ambients and vertical jets will be discussed.

Albertson et al. [8] conducted measurements in order to verify mathematical models and to determine the value of the entrainment constant. They found that for non-buoyant jets ($F = \infty$), the appropriate value of α was 0.057. Other researchers have been in basic agreement with that figure. Albertson also found that the centerline velocity decayed as 1/S (that is, inversely as the streamwise coordinate) for pure momentum jets and that the half width increased directly as the streamwise coordinate. These dependencies are consistent with the derivations involving mixing length hypotheses found in Schlichting [5]. The assumption of the

Gaussian velocity profile in the Zone of Established Flow was also confirmed.

For pure buoyant plumes Abraham [9] proposed a value of Ø.Ø85. List and Imberger [1Ø] and Fan [11] recommended Ø.Ø82 for the value of the entrainment constant for pure buoyant plumes. Fan also recommended Ø.Ø57 for momentum jets.

In an effort to model jets which were neither pure momentum jets or buoyant plumes, Morton et al. [7] proposed that the entrainment constant be given by:

$$\alpha = 0.057 + a_2/F_L$$

Hirst [12] proposed a value of Ø.97 for a_2 and that the sine of the angle of inclination of the jet to the horizontal should be included on the correction term also.

Davis et al. [13] suggest the entrainment coefficient be given by:

$$\alpha = 0.057 + 0.083/F^{0.3}$$

They also measured the decay of centerline jet velocity with streamwise coordinate as well as the growth of the jet dimensions. Their apparatus discharged a saline jet downward into fresh water, and they used hot film anemometry for measuring velocity. No firm correlation was reached with respect to jet growth because of the scatter of the data. Their velocity decay data showed a decrease in the rate of decay with decreasing Froude number. This is consistent with the data from Albertson's studies for infinite Froude number and that of Rouse et al. [14] who reported that the centerline velocity for a pure buoyant plume decayed as $S^{-1/3}$. Davis also verified the Gaussian nature of the velocity distribution in the Zone of Established Flow.

C. SUMMARY OF PREDICTED BEHAVIOR

Based on the foregoing, the jet behavior observed through Laser Velocimetry is expected to be predictable. Specifically, the jet is expected to grow in the half width, B, at a rate proportional to the streamwise coordinate, S. The centerline velocity is expected to decay at a rate proportional to 1/S for the pure momentum case and to $S^{-1/3}$ for the pure buoyant case. By fitting the observed jet velocity field to appropriate power-law relations, an expression for the volumetric flow rate Q as a function of streamwise coordinate can be obtained. This expression can then be differentiated with respect to S to obtain the entrainment rate. As B and U_m are known, the value of the entrainment coefficient at any level can be calculated. A mean entrainment coefficient can then be obtained for each jet and compared with theory. Values of mean entrainment coefficient are expected to vary between 0.057 and 0.082.

IV. APPARATUS AND PROCEDURES

The present work represents the first in a series of studies investigating the characteristics of turbulent buoyant jets using Laser Velocimetry. As such the present research concentrated on the development and validation of the technique. This leads to a developmental approach to the use of the LDV and to the techniques of measurement employed. Also, the LDV progressed through several evolutionary stages during the course of the work as the methods used were refined and problems with original approaches were identified and corrected.

The information presented in this chapter is the result of a number of changes to the original apparatus and approaches to the employment of the LDV. It reflects the form of the experimental arrangement and the method of use which proved to be most effective in measuring the fluid velocities.

A. LASER DOPPLER VELOCIMETER OPTICS

The LDV used in the present work was a TSI, Incorporated model 9100-5 Laser Doppler Velocimeter. It is a modular instrument which is intended to be user assembled with components included as required for the application. All components are mounted on an anodized aluminum base which is equipped with mounting brackets for securing the modules to the base. The optical modules are secured to each other by the means of thumb screws and the entire assembly is mounted on the base on rotating mounts which permit the choice of angle of velocity component to be measured. Figure 5 presents a schematic representation of the LDV optical assembly.

The laser unit is mounted in the lower part of the extruded base. It is a Spectra Physics 15 milliwatt Helium-Neon laser which operates in the continuous wave (CW) mode. Power to the laser is furnished through a separate power supply. The LDV is assembled with the laser unit pointing away from the test section. The laser beam is focused onto a front-surface mirror located in a housing at the end of the base which reflects it to a similar mirror at the top of the housing from which it is reflected in the direction of the test section. Both of the mirrors are provided with adjusting knobs which act through wedge assemblies to permit alignment of the beam.

From the top front-surface mirror, the beam is focused on an aperture located in the center of the after rotating mount for the optics assembly. It then passes to a prismatic beam-splitter module which separates the single beam into two coherent beams of equal intensity which travel in parallel paths down the base.

The two parallel beams then enter the frequency shifting module. It contains two Bragg Cells, one in the path of each of the beams. The Bragg Cells are acoustically vibrated by electrical signals provided from a frequency shift unit and power amplifier located remotely from the base. One cell is driven at 40 MHz and the other at a frequency above the first by an amount selectable by pushbuttons on the frequency shift unit. Each Bragg Cell is followed by a beam steering lens eccentrically mounted in wedge assemblies. These lenses can be rotated to realign the beams, to correct for the deviation introduced by the frequency shifting process. In addition, the next module, the beam steering module contains another such assembly in the path of one beam. This is provided to assist in beam crossing during final alignment of the device.

The next module, the receiving optics unit, contains another rotating mount assembly. As the beams proceed towards the test section, they travel through passages in the outer portion of the assembly.

Following the receiving optics assembly a beam expander is installed if the beam separation to be used was 50 mm. If the beam expander module is omitted, the beam separation is 22 mm. The latter was selected for the present work because it provides a superior signal-to-noise ratio and a smaller intersection volume with the selected transmitting lens than does the 50 mm separation. This module is followed by a beam-stop assembly, a third and final rotating mount and the transmitting/receiving lens.

The purpose of the beam-stop assembly is to block out unwanted orders of the diffraction pattern created by the Bragg Cells. The order used is the plus first order beam, in which the proper difference in frequency exists. The unshifted components (zeroth order) and those of higher order must be blocked in order for a proper Doppler shifted signal to be provided.

The lens used for this study has a focal length of 120 mm. Other sizes are available from TSI, extending in focal length up to 600 mm for the model 9100-5. In the present work, it was found that the increase in the length of the intersection volume and the lowering of signal-to-noise ratio which result from the use of the longer focal length lens or greater beam separation degraded the quality of measurement. Accordingly, the final configuration selected was the 120 mm focal length lens with the 22 mm beam spacing. Since 180 degree backscatter is the intended mode for this device, the transmitting lens is also the receiving lens.

The focusing action of the transmitting lens causes the beams to cross, forming an intersection volume. Light scattered from the intersection volume by particles flowing in the fluid is gathered by the same lens and passed back down the axis of the LDV. It is focused by a lens in the receiving optics assembly on an aperture, then refocused by another lens to the photomultiplier tube by way of a mirror. The aperture is located in a holder assembly and can be changed providing larger or smaller size holes.

B. THE LASER DOPPLER VELOCIMETER ELECTRONICS

The optics assemblies, when properly aligned, cause the image of the intersection volume of the two laser beams to be focused on the detector surface of a photomultiplier tube. This tube is powered by an external power supply equipped with an adjustable gain control. It is also provided with a self protection feature to prevent "cooking" the tube should the light intensities encountered be greater than appropriate for the selected gain. The photomultiplier tube converts the variations in the intensity of the light signal emanating from the intersection volume into a voltage signal varying at the same frequency. This signal is the raw Doppler signal from which the velocity can be determined. Figure 6 shows typical Doppler bursts both with and without the pedestal signal component.

The Doppler burst is caused by the variation in intensity of the light scattered as a particle passes through the laser beam intersection volume. Passage of a single particle through the ellipsoidal volume illuminated by the fringe pattern causes light to scatter, varying in intensity at a rate corresponding to the rate at which the bright fringes were encountered. The frequency of the optical signal thus created is the differential Doppler frequency, a knowledge of which permits computation of the particle velocity. The envelope of the Doppler signal is the total length of time occupied by one burst as shown in Figure 6. A burst is defined as the signal generated by the passage of one particle through the laser beam intersection volume.

The photodetector output is sent to the Counter for processing. It consists of three distinct sections; the input conditioner, the timer, and the display section. For the present work, only the first two sections were directly employed.

The input conditioner's function is to take the raw signal from the photomultiplier tube and generate either one or two measurable envelopes for the timer to use, depending on the mode of operation selected. The N-cycle mode was used in the present work. In this mode, the input conditioner generates a signal the envelope of which is of the same duration as the Doppler burst consisting of N cycles. Here N refers to the number of cycles which has been selected on the front panel to be measured in a burst from one particle passing through the intersection volume. A second envelope is generated of time equal to that for N/2 cycles to pass. The N/2 cycle envelope is used to validate the data during processing. These envelopes are generated through the use of Schmitt triggers and threshold detecting circuitry. A full discussion of the electronics involved is beyond the scope of this work. For further information refer to the manufacturer's technical documentation for the LDV [15].

In the total burst mode, which was not used in this study, the input conditioner generates one envelope, corresponding to the time of the total burst. Circuitry is included to allow counting the number of cycles in the burst. This mode is useful if the data rate is low and correction for velocity biasing is required.

The input conditioner also contains filtering circuitry for the removal of the pedestal component of the signal (the low limit filter) and for the isolation of noise from the signal of interest (the high filter). These are adjusted in combination to provide a signal which is free of spurious noise while still allowing enough of the signal to pass to adequately measure the flow fluctuations. Additionally, an amplitude limit control is provided. Its function is to reject signals of greater than a specified amplitude. This has the effect of eliminating signals from larger particles which may not be adequately following the flow.

The final control on the input conditioner is a selector which provides control of the number of cycles used in the N-cycle mode and the minimum cycles required for a valid burst in the total burst mode. Additional fittings include jacks for the photomultiplier output signal and filtered output monitor for use on an oscilloscope.

The timer utilizes a high speed digital clock operating at a frequency of 250 MHz and with a temporal resolution of 1 nsec. When the envelope signal from the input conditioner is gated into the clock, the time for the envelopes to pass is measured. In the N-cycle mode, the time for N cycles was compared to the time for N/2 cycles via a direct division. If the deviation from double the N/2 time exceeds the percentage selected by switch on the front panel the burst is discarded. This comparison is not used in the total burst mode.

On the front panel of the timer section output jacks for the analog output and direct digital signal output are found. Additionally, selector buttons and lights indicating active values are found for the exponent to be applied to the time signal in the interpretation formula. The selection of the exponent value can be either manual or automatic; however, when autoranging is selected, a stable signal frequently can not be obtained. Accordingly, in the N-cycle mode in particular, the LDV should be operated in the manual mode once the magnitude of the exponent for the current flow level has been experimentally determined. Autoranging should be used in the total burst mode because of the wide range of the numbers of cycles and the time for the burst which will be detected.

The front panel of the timer also contains a standard ICC/Cannon 37 pin connector for transmission of control and readout information directly to a digital computer. The signals which are available via this connection are as follows:

1. A 16 bit word consisting of a 12 bit mantissa and a 4 bit exponent representative of time for the burst.
2. An 8 bit word for the representation of the number of cycles in the burst. This would be useful in the total burst mode.
3. A one bit data ready signal for computer handshaking.
4. A one bit data hold signal.
5. A one bit single measurement per burst signal. This can be used for control of some LDV functions from a remote location.

C. THE COMPUTER AND SUPPORTING ELECTRONICS

The computer used to control data acquisition is a Hewlett-Packard 9826 microcomputer. It uses a 16-bit word length and is capable of communicating directly with the LDV via an interface bus arrangement. Because of the 16 bit word length, the data transfer arrangement used in the present work is only appropriate for the N-cycle mode. This is because there is no arrangement to hold data from the digital word representing the number of cycles for later input to the computer. Using the N-cycle mode, the number of cycles per burst to be measured is entered by the operator at the computer console. This particular HP9826 is fitted with a standard RS-232C interface and acquired data is transmitted via modem to a larger computer for reduction. In the interim, the experimental information is stored on flexible disks.

For any work involving laser velocimetry, it is essential that the operator be able to monitor the quality of the signal being processed. For this purpose an oscilloscope is irreplaceable. In the present work a recording oscilloscope capable of dual trace operations and with an operating range of up to 10 MHz was used. In general for use in LDV applications, a frequency capability of up to 100 MHz is desirable.

A frequency generator is required for setup and checkout of the LDV electronics. It should be capable of up to 1 MHz output and was sufficiently precise that a stable velocity reading can be generated.

D. THE SIGNAL PATH

When a particle passes through the intersection volume of a differential Doppler LDV, such as this one, the light scattered in all directions is modulated at the differential Doppler frequency. A lower frequency modulation due to the variation in light intensity across the beams is also present and constitutes the pedestal. The light scattered from the intersection volume is focused onto the photomultiplier tube by the receiving optics. The photomultiplier tube converts this optical signal to an electrical signal with a voltage proportional to the intensity of the light. This photomultiplier tube output is passed to the input conditioner.

On arrival at the input conditioner, the signal is first checked by the amplitude limiting circuitry which eliminates any bursts of excessive amplitude. For the purposes of the current work, the amplitude limit was not set because the quality of the data gathered indicated that no particles sufficiently large to affect accuracy were being processed.

Next the signal is filtered, first by the high pass filter which is set to eliminate the low frequency component of the signal, the pedestal. The low pass filter next removes components of frequency higher than its setting, which eliminates shot noise in the photomultiplier tube and thermal source interference. The signal is then ready for processing by the Schmitt trigger system for generation of the envelopes.

This new signal is passed to the timer where the leading and trailing edges of the envelope are gated by the timer and the signal representing the time of the burst is generated. From here, the output is passed to the display section and to the output jacks for the digital or analog output. In the present work the signal was read off of the

37 pin connector in the front panel and processed by the HP9826.

The signal received by the HP9826 is not directly interpretable as the time, but yields the Doppler frequency when used in the following formula:

$$f_d = (N \times 10^9)/(D_m \times 2^{n-3})$$

Here D_m is the value of the mantissa of the 16 bit computer word, f_d is the differential Doppler frequency, n is the exponent part of the 16 bit computer word, and N is the number of cycles in the burst, which is entered by the operator on program initialization and set on the front panel of the counter.

The computer program under which the process is controlled applies the foregoing formula and computes the velocity represented by the sample using the geometry of the LDV and the following formula:

$$v = \lambda f/\{2\sin(\theta/2)\}$$

Position and orientation data, as well as temperature of jet and ambient fluid, are entered manually during data acquisition. All quantities are stored on disk in a logical format which is directly transferred to the VAX mainframe computer via the telephone line. It is processed there using statistical methods to extract the mean velocity, jet half width, and entrainment coefficients. If desired, the turbulence intensities and normal component of velocity can be measured and processed using the computer programs developed in the present work.

The flow of the signal is schematically represented in Figure 7.

E. THE FLUID LOOP

The jet studied for the present work was generated in a tank measuring 0.625 X 0.333 X 0.476 meters. The depth of the water in the tank was 0.419 meters. The walls of the tank were constructed of 0.00635 meters thick glass. Flow was provided by a centrifugal pump via a control valve, a heater and calibrated rotameter to a nozzle 0.003175 meters in diameter. The nozzle was located in the tank 0.067 meters from the nearest wall, a distance of 21 diameters.

Temperature was monitored by two thermocouples, the first embedded in the nozzle block for the measurement of the temperature of the effluent. The other was located in the bulk of the fluid in the tank for the measurement of the ambient temperature.

Early experiments revealed that significant amounts of heat accumulated in the tank from the injection of the warmer water in the jet, with the result that the temperature could not be held constant during the course of an experiment. The situation was corrected by the installation in the tank of a cooling coil connected to a constant temperature bath. Subsequent to the installation of the coils, the temperature remained constant in the tank over the course of the experiments to within 1 degree Fahrenheit. It should be noted that the presence of the coil created temperature gradients in the tank, and a better system of temperature control should be found for use in experiments which may require more precise information on the ambient temperature fields than was required in the present work.

Early experiments also indicated that significant circulatory effects were generated in the tank when flow rates in excess of 40 percent of full scale on the rotameter were used. Accordingly, flow rates below that point were maintained for all later work.

Figure 8 is a schematic of the fluid loop used in this work.

F. POSITIONING APPARATUS

Positional control and support for the LDV were provided by a milling machine table from which the machine head had been removed. This arrangement allowed the LDV to be positioned reproduceably to within 0.0000254 m, (.001 inches), spatially. It was also sufficiently massive that vibration was minor, and could therefore be discounted as a source of significant error.

While the movement of the milling machine provided good control, some hysteresis was present in the left-right, and fore-aft movements. This effect was minimized by always approaching desired position in the same direction. Checks of the method resulted in good accuracy being demonstrated.

G. DATA ACQUISITION PROCEDURES

Flow rates and trace locations for the data acquisition were selected to provide similar conditions to previous studies in order to compare results and validate the technique. While an infinite Froude number initially appeared to be the best choice, it was unobtainable with the experimental apparatus. Relatively high Froude numbers, on the order 200 to 500 were easily attainable and were hence used.

The height of the first trace was selected to remain beyond the accepted 6.2 diameters which delineates the Zone of Flow Establishment (ZFE) from the Zone of Established Flow (ZEF) in order to keep the expected velocity profiles as nearly Gaussian as possible. Velocity traces were obtained at regular intervals to ease positioning. The number of points in the trace was selected to provide a wide base on which the curve fit routines could operate, as was the number of traces made in a given experiment.

For seeding of the flow field, several substances were tried without success before powdered alumina was found to provide very good reflectivity, uniform (relatively) particle size, and good flow-following characteristics. Also of concern was the abrasive characteristics of a seeding particle in the centrifugal pump. The seeding particle recommended by TSI is silicon carbide, but its specific gravity is greater than that of alumina and its increased abrasive qualities were believed to be potentially prohibitive, as was its cost.

In preparation for data acquisition, the flowmeter was calibrated using a graduated container and stopwatch. Calibration curves were constructed and the data fit to a cubic equation to allow computer determination of the exit centerline velocity. Analytic expressions for the density and viscosity of water were also utilized to provide Reynolds number and Froude number data during computer calculations.

The alignment of this Laser Doppler Velocimeter proved to be extremely sensitive to changes in location of the base and to changes in the angles of the Bragg Cells. While it was not necessary to repeat the entire alignment process for each experiment, it was essential that beam concentricity, beam crossing and power maximization be checked if signal quality deteriorated. Once beam crossing had been achieved at one LDV orientation, the device was rotated 90 degrees to assure that the beams still crossed and that the intersection volume had not changed in its position relative to the optics. The latter was easily determined by positioning the intersection volume on a scatter plate, marking the spot, and then rotating the barrel of the LDV. If the laser light moved off the spot during the rotation, realignment was necessary because of lack of concentricity. Loss of beam crossing was apparent by a total loss of Doppler signal.

Once calibration and alignment checks were complete, one step remained in preparation for data acquisition. This was the establishment of the spatial reference for the intersection volume. The center of the nozzle exit was chosen as the origin of the coordinate system. It was located by finding the coordinates of the extrema of the nozzle structure in all three directions and then applying knowledge of the nozzle geometry to find the center. The edges of the nozzle were found by observing the filtered output of the photomultiplier signal on the oscilloscope. When the intersection volume was precisely centered on the knife edge of the nozzle, the signal observed on the oscilloscope was a sinusoid of frequency equal to the applied frequency shift. A maximum amplitude indicated the center of the intersection volume was at the reflective surface.

After initialization of the data acquisition program on the HP9826, the LDV was positioned in the test section. The frequency shift was selected so that the whole range of flow reversals anticipated could be measured. For the present work a frequency shift of 500 kHz provided excellent results. Next, the low filter was adjusted to remove the pedestal while observing the bursts on the oscilloscope. Occasionally, the pedestal was not visible through noise in the signal initially. In that case the high filter was adjusted first to eliminate enough to see the Doppler signal. Final filter adjustment was largely a matter of judgement with respect to how wide the bandpass characteristics should be set to pass the range of signals characteristic of a turbulent flow.

After the signal quality had been optimized by the filter adjustment, the data acquisition proceeded. Provision has been made in the data acquisition program on the HP9826 to display the "spectrum" of the velocity data being accumulated. The display also can be be zeroed at any time to erase accumulated data. The display was monitored to observe the distribution of the velocities to monitor data quality. If several peaks appeared, noise was present (the distribution should be nearly Gaussian in shape), and the filters were reset to narrow the passband. In some cases, the setting intervals on the filters were not sufficiently fine to narrow the band in the frequency range currently in use. In that case, a change in the value of the frequency shift was appropriate, and the frequency shift and filters acted together to provide appropriate range.

When signal quality and the distribution of the accumulated data indicated that good quality information was being received, the operator stored the information at that point and proceeded to the next. When to store data was determined by the number of samples desired for the statistical base and the quality of the signals being processed. In the present work, the statistical base desired was a minimum of 100 data points at each location. Early experiments provided good experience in filter setting and selection of the frequency shift, and little trouble was experienced in later experiments in obtaining both good signal quality and a Gaussian distribution of the velocity spectrum during acquisition.

Several experiments could be conducted without the necessity of completely reducing the data for any previous ones. The time required to gather data on one velocity component in a jet at five levels and seven to nine positions on each level was about one day. The number of points which were measured for each experiment was limited simply by the time over which conditions remain constant in the apparatus.

H. DATA REDUCTION

Computer programs were developed for data transfer and reduction as well as the acquisition control process. These programs were modularized to the extent practical in order to provide maximum flexibility in application to later research. Functionally, the programs can be classified as acquisition, transfer, intermediate reduction, and final reduction.

The acquisition program resided exclusively in the HP9826. Its function was to automate the gathering of the experimental data and to convert raw time data into velocity. Additionally, the acquisition program recorded the relative coordinates at which each sample was taken, the orientation of the LDV for the data set, the flow meter reading, the temperatures of effluent and bulk fluids, the date of the experiment, and identifying information for the data set. Its final output was a set of files on flexible disk numbered by experiment number and data set within the experiment.

Data transfer programs were necessary on both the HP9826 and the VAX computer. They acted in conjunction, communicating over telephone lines to transfer the files from floppy disk to internal storage in the mainframe. The process was automatic and progressed without operator intervention once program execution began as long as all files to be transferred resided on the same flexible disk.

If a particularly long experiment was spread over more than one disk, the operator reinitialized the process in order to change to the new one.

The purpose of the intermediate reduction program on the VAX was to consolidate the information contained in the separate data files associated with an experiment into one file. In the process, the velocity data was processed statistically, applying Chauvenet's criterion to reject data values which deviated excessively from the Normal Error distribution. This program preserved and recorded all identifying data such as position and temperature, but presented the output in the form of a single file which reported the velocity data in terms of mean velocity and turbulence intensity for the components measured at each position. Because this program expected to find files for streamwise and radial components in its input data set, dummy files were included for the second component if studies were conducted in the streamwise direction, only. This was most easily done in the data acquisition phase of the process.

Final data reduction was accomplished using a program which was applicable to the study of axisymmetric jets in a quiescent ambient only. It arrived at values of B, the jet halfwidth, and U_m, the jet centerline velocity, by fitting the data from each trace directly to an equation for a Gaussian profile. The values of these quantities for each trace were then fitted to power law curves to arrive at expressions for each as a function of the streamwise coordinate.

The assumption of the Gaussian profile enabled easy integration to obtain a simple expression for the volumetric flow rate in the jet, Q, at each level as a function of centerline velocity and jet half width. As each of these was now a known function of the streamwise coordinate, substitution and differentiation with respect to S yielded directly an expression for the entrainment coefficient. The coefficients obtained from the power fits were used to compute local values of α and to arrive at a mean value and standard deviation for use in comparisons.

The final reduction program also computed the values of the exit Froude Number and Reynolds Number using properties calculated from accepted analytic expressions. All results were tabulated in program output including coefficients of determination for curve fits and values of standard deviation for quantities for which means were computed.

V. CONCLUSIONS AND RECOMMENDATIONS

Ten experiments were conducted during the course of the present work. Additionally, many sample traces were made and trial measurements were taken for the purpose of selecting the optimum seeding particle, optimizing filter settings, and testing of the alignment of the LDV. Of the ten experiments, the first six served to develop the technique to be used and to debug both the apparatus and the data acquisition computer program.

The final four experiments were conducted using the procedures refined in the previous six and constitute the trial set for comparison with previous work and validation of the technique. Items of specific interest in these experiments are the following:

1. The verification of the assumed Gaussian velocity profile over the radial cross section of the jets.
2. The decay of the jet centerline velocity with streamwise coordinate within the Zone of Established Flow.
3. The growth of the jet through entrainment of the surrounding fluid as demonstrated by the variation of jet half width, B.

4. The mean entrainment coefficient for each jet, as computed from the local values at each trace level measured.

Each of these will be addressed separately in the following sections, and numeric results are tabulated in Appendix B.

A. VERIFICATION OF THE GAUSSIAN PROFILE

Velocity traces were obtained by measuring five to ten mean velocities across the diameter of the jet at various downstream positions. Each trace's data was fit to a Gaussian curve during the first step in the final data reduction program. Figure 9 is a plot of one trace's least squares fit curve and the data from which it was constructed. This trace is typical of the data gathered, and illustrates both the goodness of the curve fit and the relative uncertainty as to the actual position in the jet at which the measurements were made.

While the centerline of the jet nozzle is considered to have been located quite accurately, examination of the data for the Gaussian fits and the curves themselves provides indication that the jet may not have been discharged exactly vertically. This could lead to some error in the maximum value of the centerline velocity obtained in lower traces, but the error will decrease in higher levels of the jet due to the spreading of the jet and the attendant decrease in the rate of change of the jet velocity radially.

As can be seen from the sample trace, the assumption of a Gaussian profile is valid to within the precision of measurement possible in a turbulent flow.

B. THE GROWTH OF JET HALFWIDTH

Figure 10 presents the behavior of the jet width as a dimensionless quantity plotted versus a non-dimensional distance down the jet axis. Experiments 8 through 10 are remarkably consistent, particularly at higher values of the streamwise coordinate. The values of the data for experiment 7 deviate in both slope and intercept for reasons which will be discussed later in the chapter.

For comparison, the predicted value of the quantity B/D using the relation proposed by Albertson [8] is plotted. The results of experiments eight through ten indicate a uniformly greater width than the model for jets of infinite Froude number. This is to be expected in view of the increased rate of entrainment which is predicted with decreasing Froude number.

C. THE DECAY OF CENTERLINE VELOCITY

The decay of the centerline velocity found in the four experiments is plotted in Figure 11, along with a curve formulated from Albertson's model for infinite Froude number. Once again, the data for the final three experiments shows remarkable consistency, and that for experiment seven deviates substantially.

The data for experiments eight through ten demonstrate a decreasing rate of decay of the centerline velocity with decreasing Froude number as evidenced by their slopes on the plot. The slopes fall between the value predicted (variation as 1/S) by Albertson for $F = \infty$ and by the variation as $S^{-1/3}$ predicted by Rouse [14] for $F = 0$. The decrease in decay rate can be explained by the effect of increasing buoyancy forces with decreasing Froude number. The experimental data presented here is considered to agree very well with theory.

Extrapolation of the plots of data in Figure 11 reveals one more item of interest. The definition of the Zone of Flow Establishment fixes the demarcation between it and the Zone of Established Flow as that point at which turbulent mixing reaches the centerline of the jet. At this point, the centerline velocity will start to decay. Applying this definition, the Zone of Established Flow can be seen to start well before the 6.2 diameters predicted by Albertson. The change is attributable to the increase in the entrainment rate for a buoyant jet over the pure momentum jet studied by Albertson.

D. THE ENTRAINMENT COEFFICIENT

Figure 12 plots the mean entrainment coefficients determined in experiments seven through ten with a curve computed from Davis's relation [13]. The values computed for experiments eight through ten continue to conform to predicted values while experiment seven deviates.

Examination of the values of entrainment coefficient computed locally in the jets shows a decrease with streamwise coordinate in all cases except for experiment eight, where it remained relatively constant. For an initially buoyant jet, the decrease in entrainment coefficient with distance is expected as the local buoyancy difference decreases. This is reflected in an increase in the local Froude number and a decrease in α which is predicted by all entrainment models. Experiment seven exhibits this behavior even while not conforming to the value predicted for the mean value of the entrainment coefficient.

A comparison of the obtained local entrainment coefficients with theory was not possible because of a lack of local temperature data. However, the maximum entrainment coefficient predicted by the model of Hirst [12] for the four experiments is 0.061, a value applicable only at the nozzle exit for experiment ten. At the earliest point measured in experiment ten, a distance of eight diameters downstream, the measured coefficient was 0.076. Since the entrainment coefficient can not increase with distance, as buoyancy forces are decreasing in that direction, data from these experiments can be seen to be at variance with the model of Hirst.

E. THE JET OVERALL VELOCITY DISTRIBUTION

Figure 13 is the distribution of velocity throughout the jet measured in experiment eight. The plot was constructed using the coefficients of the curve fits for B and U_m and the Gaussian velocity profile. It is representative of the data obtained in all four experiments. On this plot the variation of halfwidth and centerline velocity and the Gaussian distribution of velocity with radial distance can all be seen.

F. THE VARIANCE OF EXPERIMENT SEVEN

Experiment seven was conducted with the highest exit velocity of the four final trials. The flowmeter setting for this set of data was forty percent of full scale, a value which was estimated from earlier trials to be low enough to eliminate the effects of recirculation in the tank. The recirculation effects at higher velocity were observable due to the presence of the alumina seeding particles in the tank. It resulted in an ambient which, instead of being quiescent, was coflowing with the jet discharge. Entrainment coefficients in early trials were significantly lower than expected, and the rate of jet growth and decay of centerline velocity decreased as a result.

The phenomenon can be explained by considering the cause of entrainment of fluid into the jet: viscous shear at the jet boundary. The viscous shear is a function of the rate of change of fluid velocity at the point in question, and that rate of change is lower if the ambient has some component of velocity in the same direction as the jet. Reduced viscous shear results in reduced entrainment, which in turn results in a decrease in the rate of decay of centerline velocity as well as jet growth.

While no recirculation was apparent in the tank during data acquisition for experiment seven, the behavior of the jet indicates that some amount was present. Specifically, the lower rate of decay of centerline velocity and the lower growth rate of the jet dimensions indicates the lower rate of entrainment into it. This is directly reflected in the much lower values of α found.

G. RECOMMENDATIONS FOR FURTHER STUDIES

The length of the Zone of Flow Establishment is a topic for which no predictive relations have yet been developed. The Laser Doppler Velocimeter is a tool which can be effectively used to study flow field changes during the transition from establishing to established flow. It possesses the ability to be positioned precisely and will not affect the flow characteristics because of its non-intrusive nature. Further, the intersection volume can be made small enough through the selection of the proper combination of beam spacing and focal length to provide extremely fine spatial resolution of measurements.

The body of literature on turbulent buoyant plumes in cross flow environments currently in existence assumes axial symmetry of the jet. In fact this is not the case. The LDV can be used to fully characterize the flow field in this environment. For this use, however, a very fine spatial grid will have to be studied in order to yield the third component of velocity through the use of the continuity equation. This requirement renders an exact knowledge of the trajectory of the jet mandatory in order to optimize the measurement procedure. The trajectory of the jet could be determined by dye injection or by investigation of the temperature field to determine in advance the grid of positions at which the velocity should be measured. Temperature data throughout the jet would also be useful in developing exact correlations involving the local Froude number, which would be a more appropriate quantity than the exit Froude number in characterization of local behavior within the jet.

In consideration of the apparent differences reported in this report with the model of Hirst, further studies on buoyant jets discharged into a quiescent ambient should be conducted to confirm the difference and to propose an improved value for a_2, Hirst's empirical constant in the relation for entrainment coefficient as a function of Froude Number. To accomplish this with accuracy, a larger tank and improved system for flow control should be installed to improve reproduceability of the settings and provide for a more nearly infinite ambient into which the jet may be discharged. A larger tank would also obviate the need for a system for the removal of heat from the tank, thus removing the artificial temperature gradients introduced to the system by the coil. A system for measurement of the temperature field should also be installed to provide for determination of the local Froude number.

H. SUMMARY

The Laser Doppler Velocimeter is a viable and accurate tool for measurement of the velocity distribution in turbulent buoyant jets. The studies conducted during the present work showed good agreement with the results obtained by other methods in separate studies. Inaccuracies in the results can be attributed to non-availability of specific data (e.g. local temperature) or to imprecision of the positioning mechanism or metering devices used, and not to the LDV itself.

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APPENDIX A

ANALYSIS OF ERRORS

Error analysis for the present work is accomplished in three levels. The first of these is the determination of the precision to which basic quantities such as spatial location and time can specified. Where available, the tolerances reported in the manufacturer's specifications for the device have been used as the source. If the quantity can not be determined from the technical documentation, the precision has been estimated from the fineness of scale or reference used in the operation of the equipment. The basic quantities and their estimated error are as follows:

1. Time (Counter-Tracker), 1 nsec.
2. Time (flowmeter calibration), Ø.1 sec.
3. Volume (flowmeter calibration), 5% of the quantity measured (1ØØØ ml)
4. Spatial location, Ø.ØØ1 inches (2.54×10^{-5} meters)
5. Beam separation at the transmitting lens, Ø.1 mm.
6. Focal length of the transmitting lens, Ø.Ø5 mm.
7. Laser light wavelength, 5.0×10^{-12} m.

For the second level of analysis, the uncertainties of the variables which were computed from formulas involving the basic quantities were estimated using the method of Kline and McClintock [16]. The uncertainties are:

1. Radial position in the jet (left to right), Ø.11Ø mm.
2. Streamwise position in the jet, Ø.11Ø mm.
3. Radial position in the jet (in and out), Ø.2Ø5 mm.
4. Mean flow velocity, (flow meter), 5% of the scale reading.
5. Beam crossing half angle, Ø.ØØØ819 radians.
6. Frequency of the Laser Doppler signal, 62.5 Hz at a signal frequency of 1 MHz.
7. Particle velocity, Ø.Ø32 m/sec at a signal frequency of 1 MHz, corresponding to a velocity of 3.5Ø m/sec. or approximately 1% of the velocity.

For the third level of analysis, the root mean square error between the curve fit computed values and the input data values for U_m and B, both at the trace to trace level and throughout the jet was computed. The standard deviation was also computed for the value of the mean entrainment coefficient. The error of the predictive equations in reproducing the data was on the order of ten percent of the value of the data point.

The percentage error expected in the values of the measured velocity using the LDV is seen to be less than one percent. The quantity is very sensitive to the precision of the alignment of the optics. The dominant factor in the computation is the error in beam separation distance.

Accordingly, it should be noted that extreme care must be taken while crossing the beams to move only in a direction perpendicular to the plane in which the beams lie. Movement within the plane of the beams will alter the crossing angle and subject the measurement process to substantial systemic errors.

The reproduceability of the positioning data is considered to be good, but the uncertainty of the actual position of the intersection volume in the jet itself is considered to exceed the values quoted for spatial accuracy. The reason for this is the indication of a deviation from vertical of the jet trajectory by as much as one degree. Accordingly, the radial location reported for the jet data points is considered to be truly accurate to within no better than one millimeter. This is considered to be the principal cause of error in the fitting of the data to Gaussian curves.

The probable presence of circulatory effects in the tank can be considered to be the primary cause of the deviation of the data for experiment 7 from predicted behavior. It should be noted that an "inversion" of the behavior of both centerline velocity and jet growth occurred in the body of the jet. Specifically, the centerline velocity increased from one level to the next, and the half width decreased. Given the accuracy of the LDV in determining velocity, it is considered that the trend accurately reflects the actual behavior of the flow field and that the change was the result of forces external to the jet itself. Similar local inversions of the expected trends were observed in jets of earlier experiments in which recirculation within the tank was clearly visible.

APPENDIX B

TABULATED RESULTS

Tabulated below are values of interest which were obtained from the curve fitting routines. The local values of the centerline velocity and jet half-widths are computed using the Gaussian profile assumptions. They were in turn fitted to the power curves yielding the equations given. The coefficients were then used to compute the value of the entrainment coefficient.

Experiment 7

Exit Froude Number 456 Exit Reynolds Number 7836
Nozzle Exit Centerline Velocity 2.54 m/sec

S (mm)	U_m (m/sec)	B(mm)
25.4	.8Ø6	3.97
5Ø.8	.725	5.79
76.2	.415	9.55
1Ø1.6	.457	8.74
127.Ø	.333	12.88

Power curve fit equation	Coefficient of Determination
$U_m = .116S^{-.549}$	.852
$B = .Ø5Ø5S^{.699}$	.934

Mean entrainment coefficient .Ø49
Standard Deviation .Ø12

Experiment 8

Exit Froude Number 365 Exit Reynolds Number 7004
Nozzle Exit Centerline Velocity 2.22 m/sec

S (mm)	U_m (m/sec)	B(mm)
25.4	.983	3.05
50.8	.543	6.59
76.2	.376	9.45
101.6	.457	12.02
127.0	.236	16.70

Power curve fit equation	Coefficient of Determination
$U_m = .0408S^{-.867}$	.996
$B = .1327S^{1.023}$	.996

Mean entrainment coefficient .073
Standard Deviation .007

Experiment 9

Exit Froude Number 317 Exit Reynolds Number 5954
Nozzle Exit Centerline Velocity 1.91 m/sec

S (mm)	U_m (m/sec)	B(mm)
25.4	.680	3.92
50.8	.534	5.80
76.2	.327	9.24
101.6	.260	12.94
127.0	.196	17.82

Power curve fit equation	Coefficient of Determination
$U_m = .0429S^{-.783}$	.944
$B = .111S^{.940}$	.965

Mean entrainment coefficient .072
Standard Deviation .008

Experiment 10

Exit Froude Number 239 Exit Reynolds Number 5123
Nozzle Exit Centerline Velocity 1.59 m/sec

S (mm)	U_m (m/sec)	B(mm)
25.4	.527	3.78
50.8	.427	6.17
76.2	.275	9.24
101.6	.203	13.90
127.0	.173	14.93

Power curve fit equation	Coefficient of Determination
$U_m = .0409S^{-.726}$	.940
$B = .0974S^{.897}$	.983

Mean entrainment coefficient .069
Standard Deviation .009

APPENDIX C

FIGURES

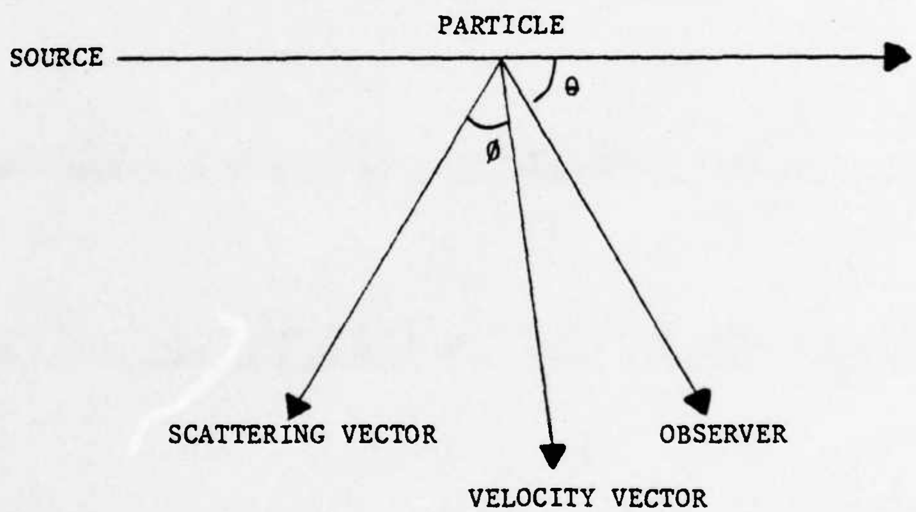


Figure 1. Geometry of Doppler Shift Model

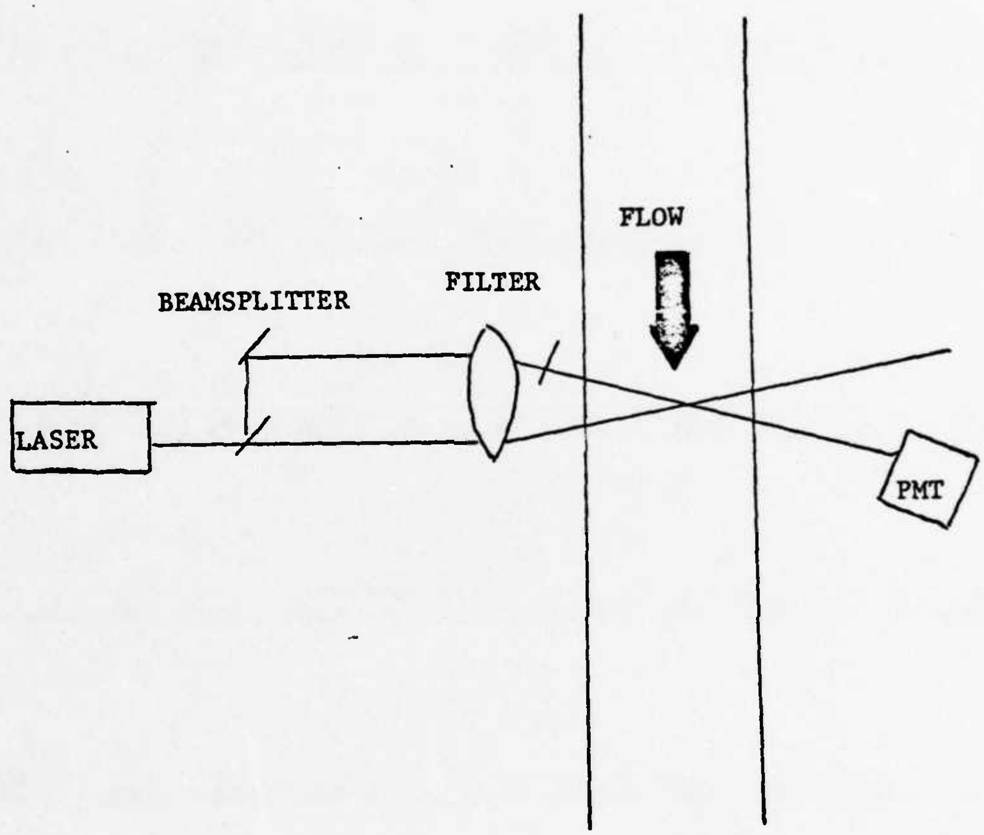


Figure 2. Typical Reference Beam LDV Arrangement

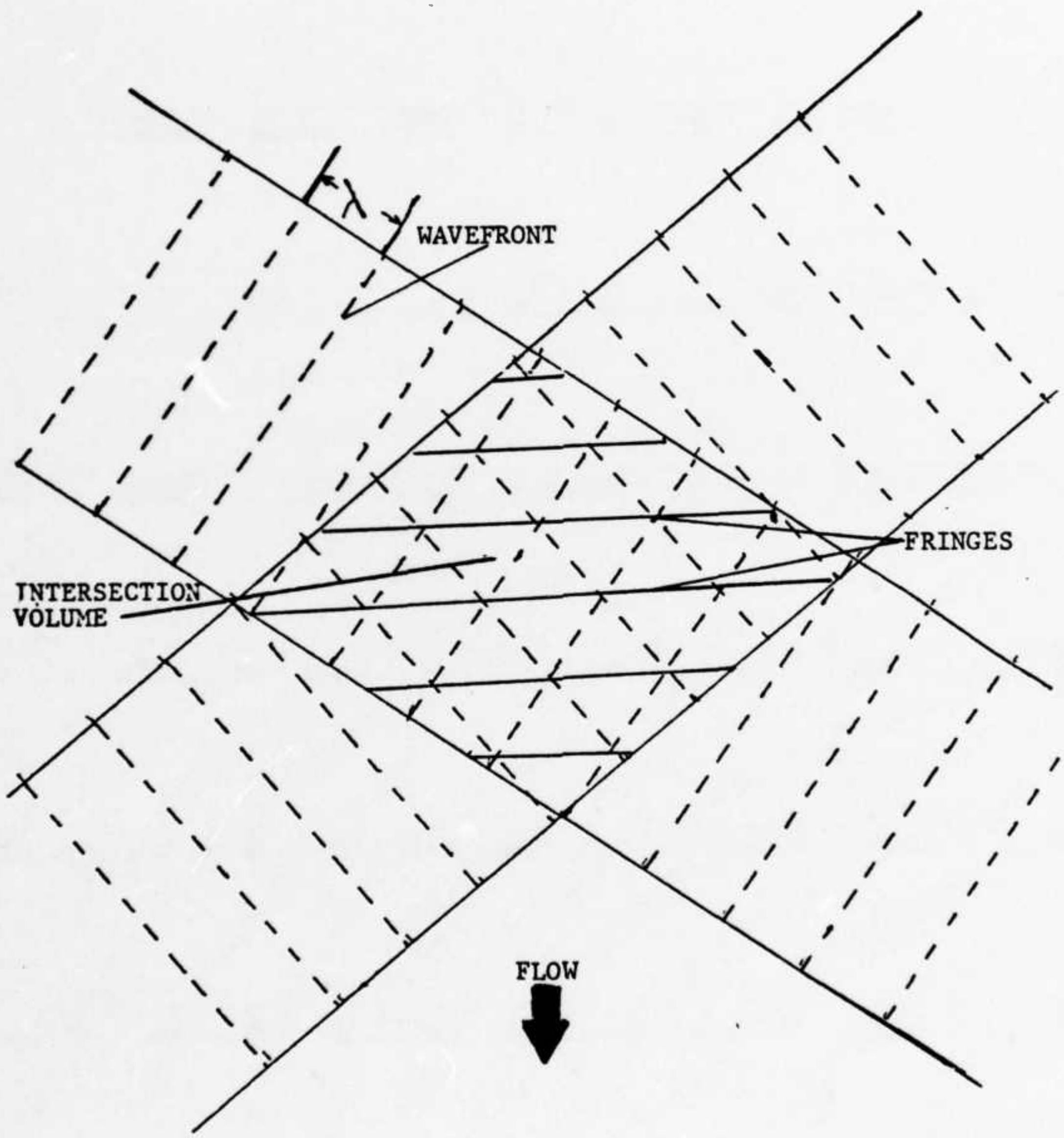


Figure 3. Fringe Model Interference

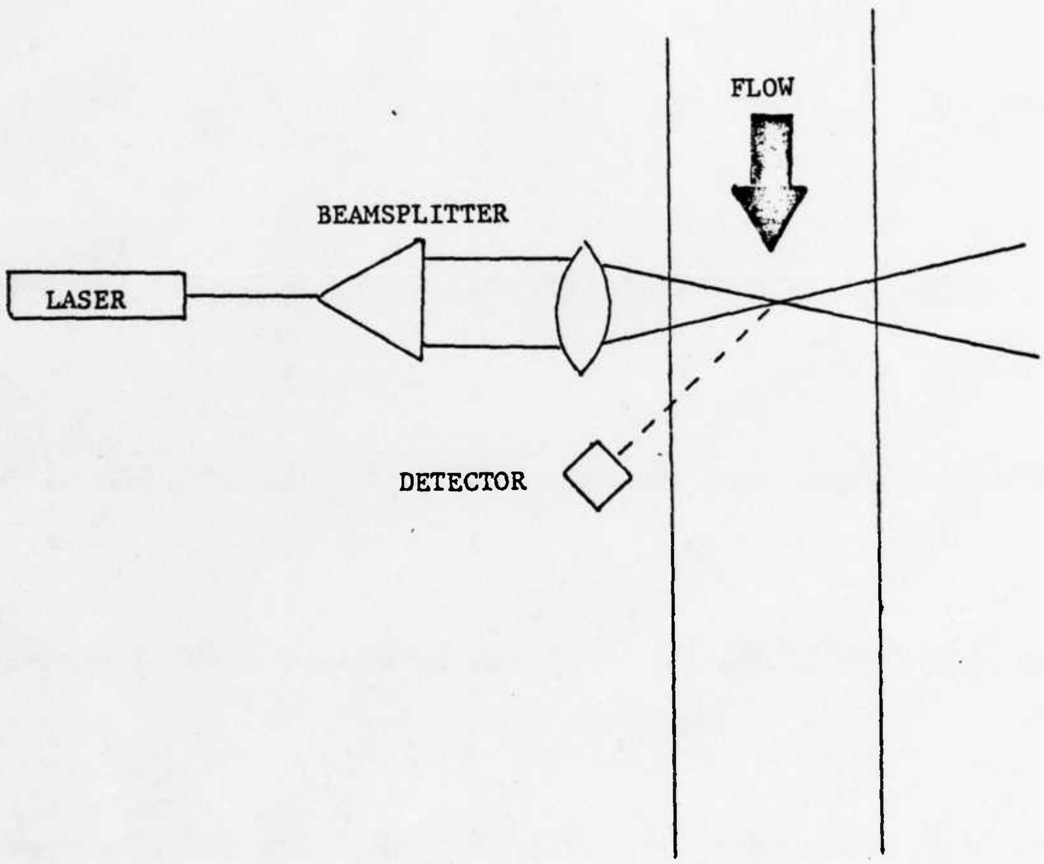
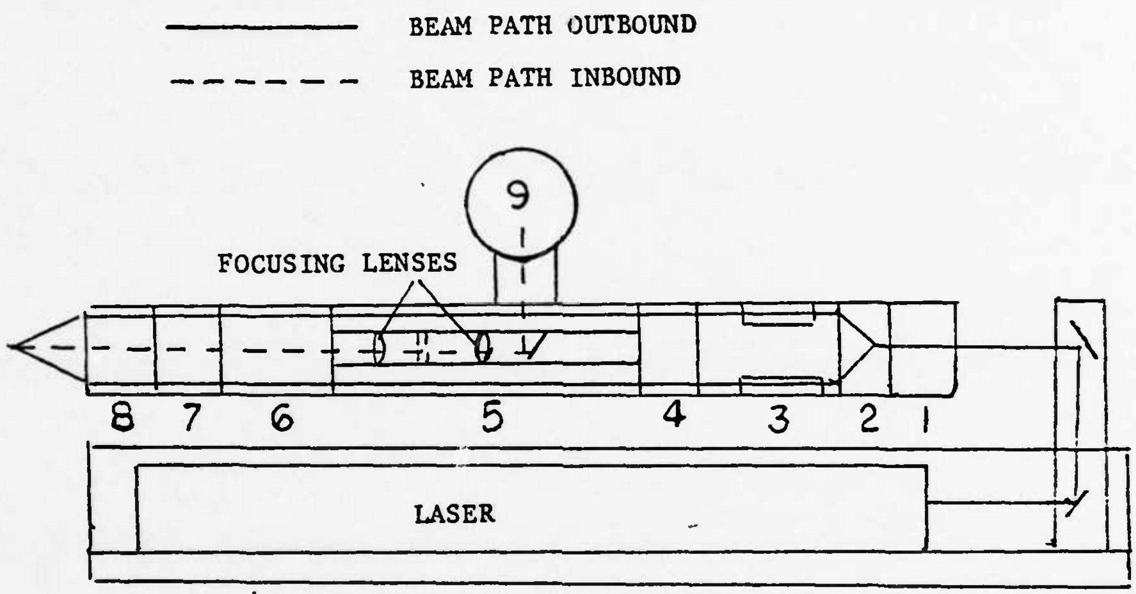


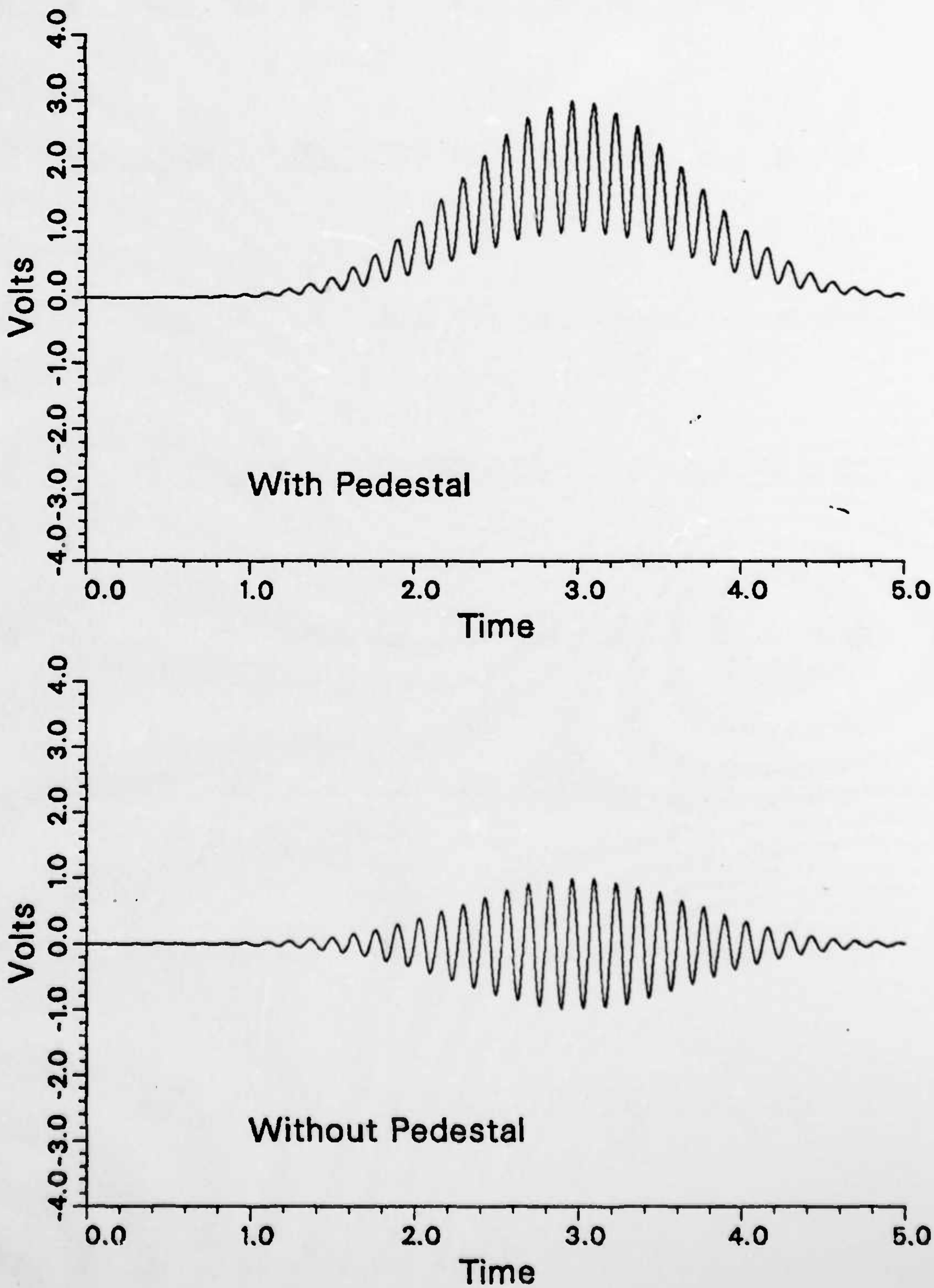
Figure 4. Typical Differential Doppler LDV Arrangement



1. APERTURE AND REAR ROTATING MOUNT
2. BEAMSPLITTER MODULE
3. FREQUENCY SHIFTING MODULE WITH BRAGG CELLS
4. BEAM STEERING MODULE
5. RECEIVING OPTICS ASSEMBLY
6. BEAM EXPANDER
7. BEAM STOP ASSEMBLY
8. TRANSMIT/RECEIVE LENS
9. PHOTOMULTIPLIER TUBE

Figure 5. LDV Optics Arrangement

Fig 6. Doppler Bursts



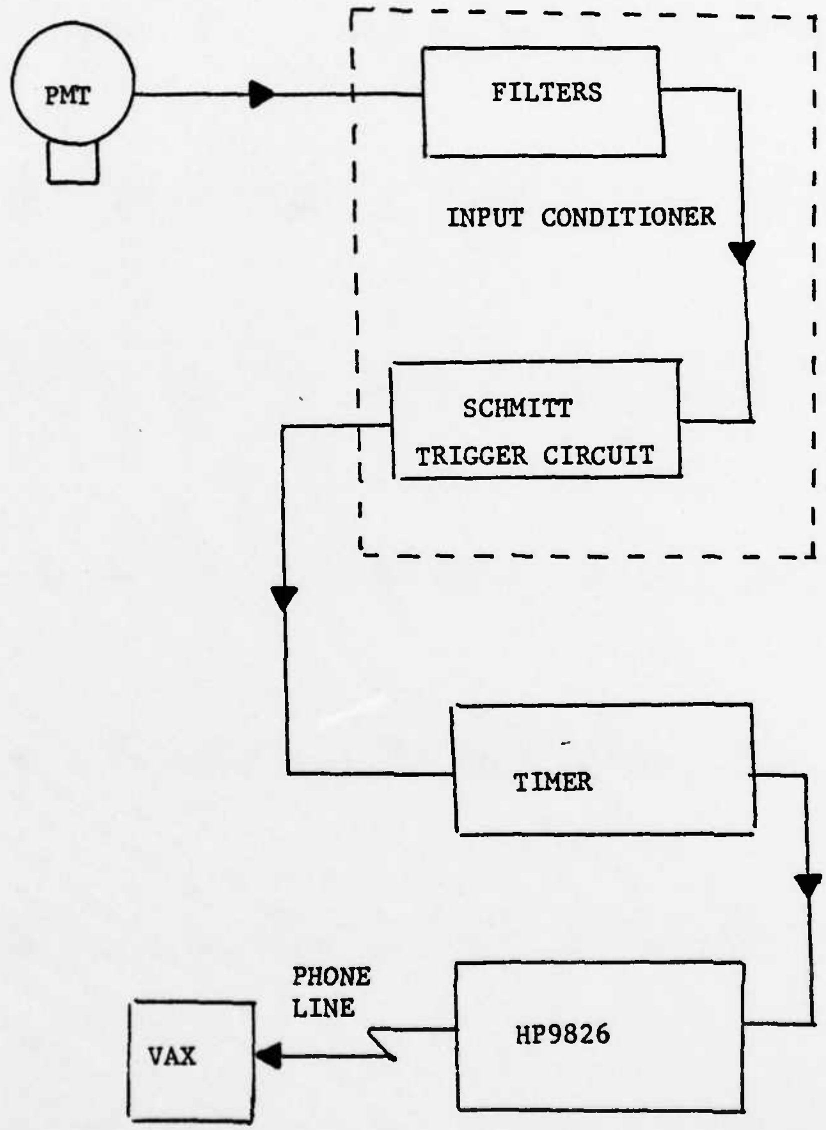


Figure 7. Signal Flow Path

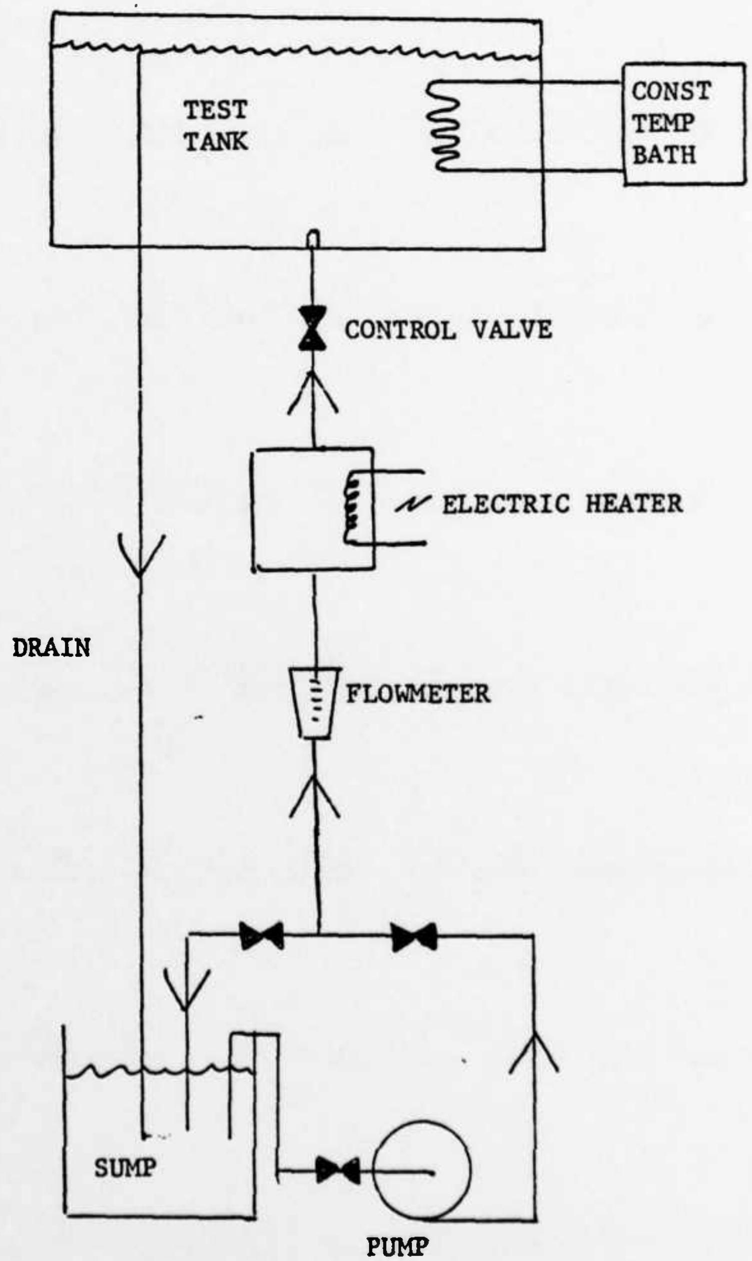


Figure 8. Experimental Apparatus Fluid Loop

Fig 9. Jet Velocity Profile

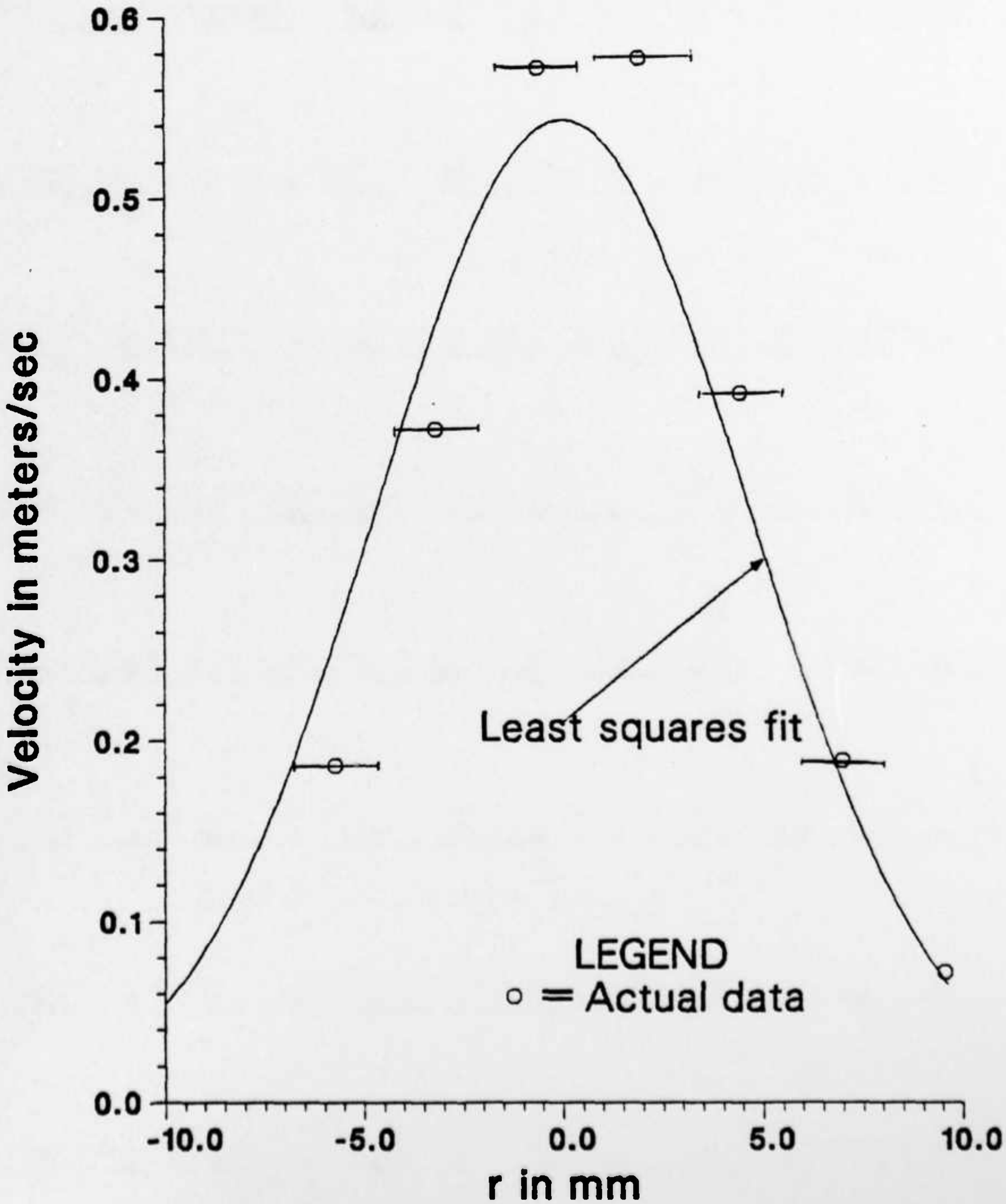


Fig 10. Growth of Jet Width

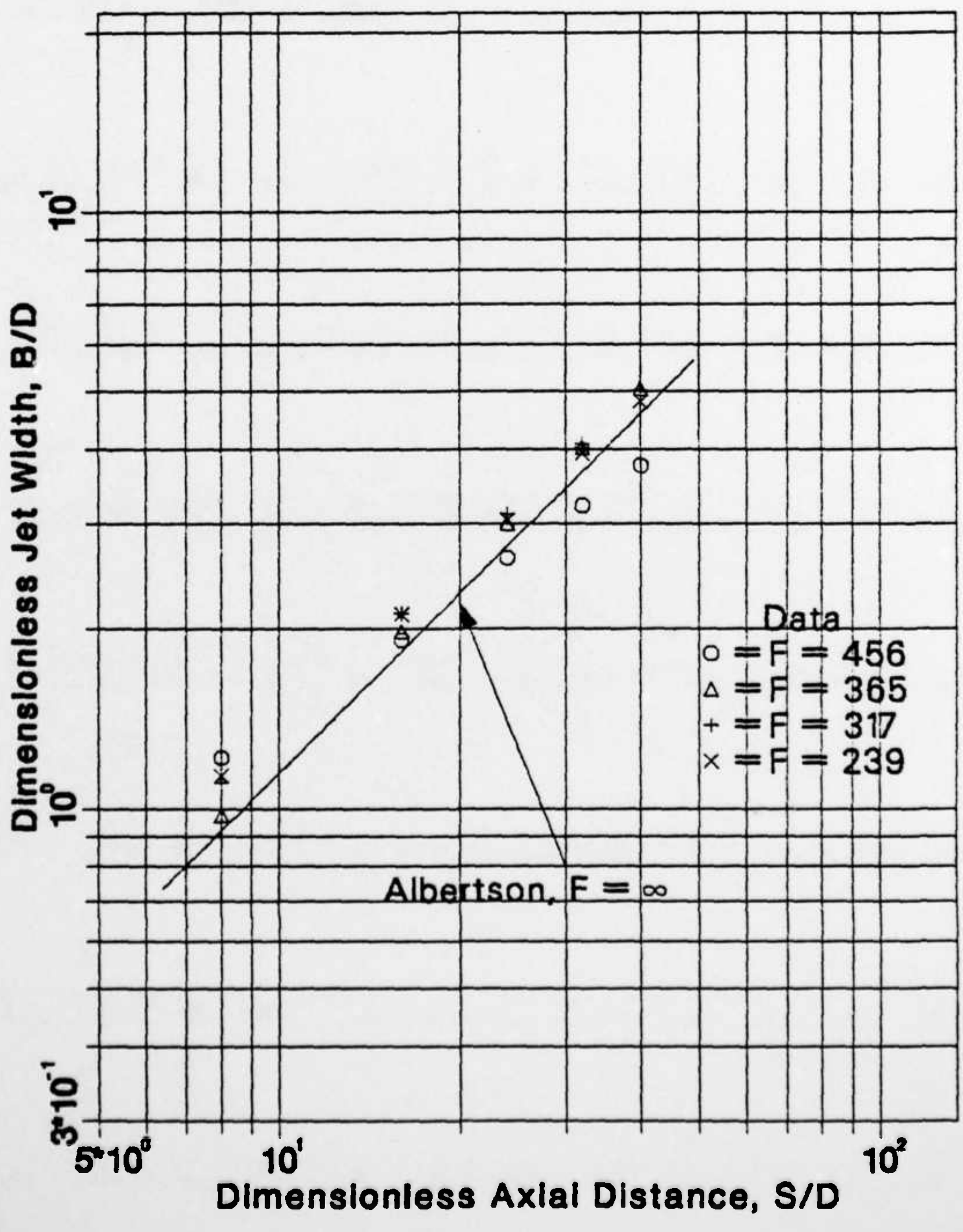


Fig 11. Velocity Decay of Jet

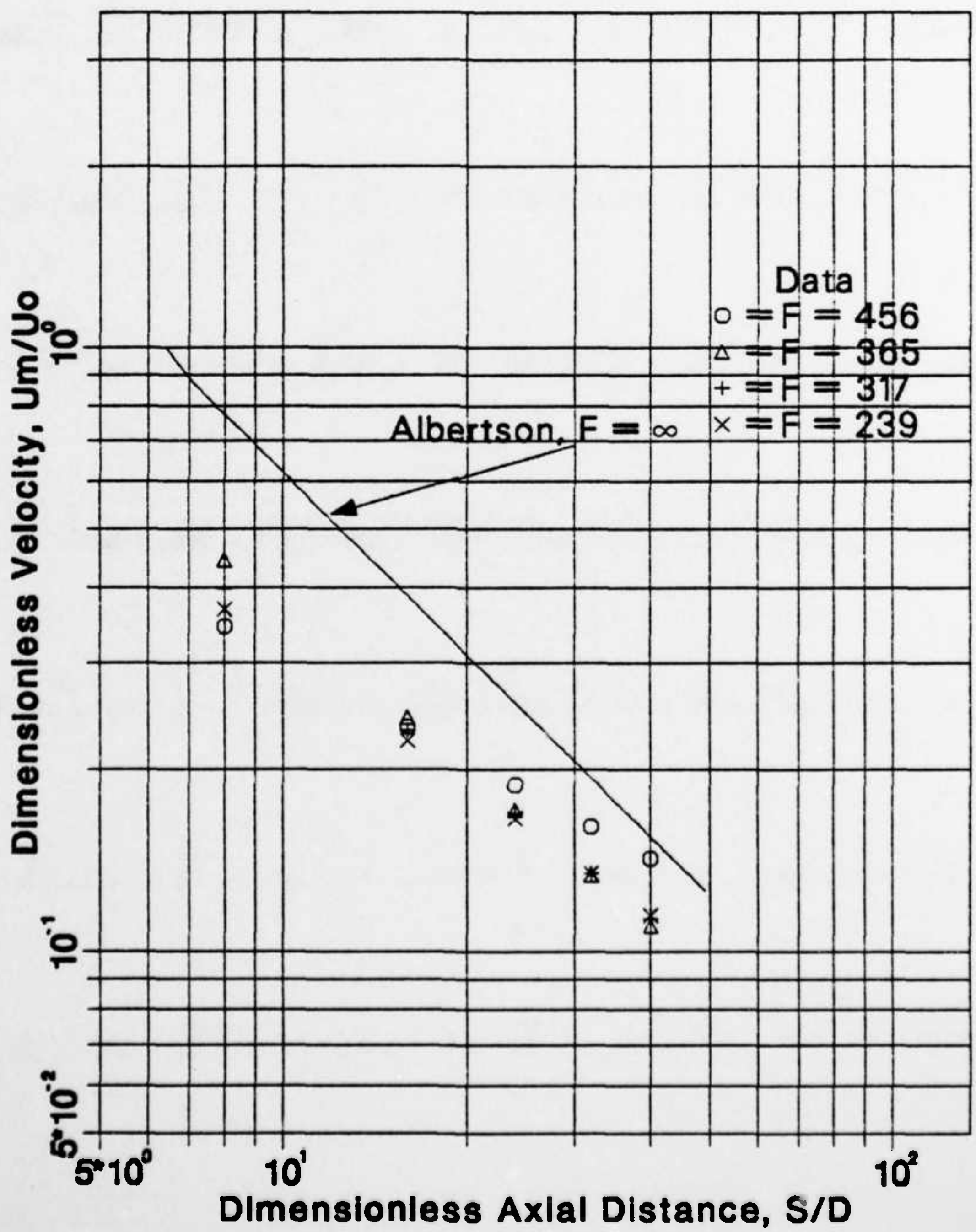


Fig. 12 Entrainment Coefficient

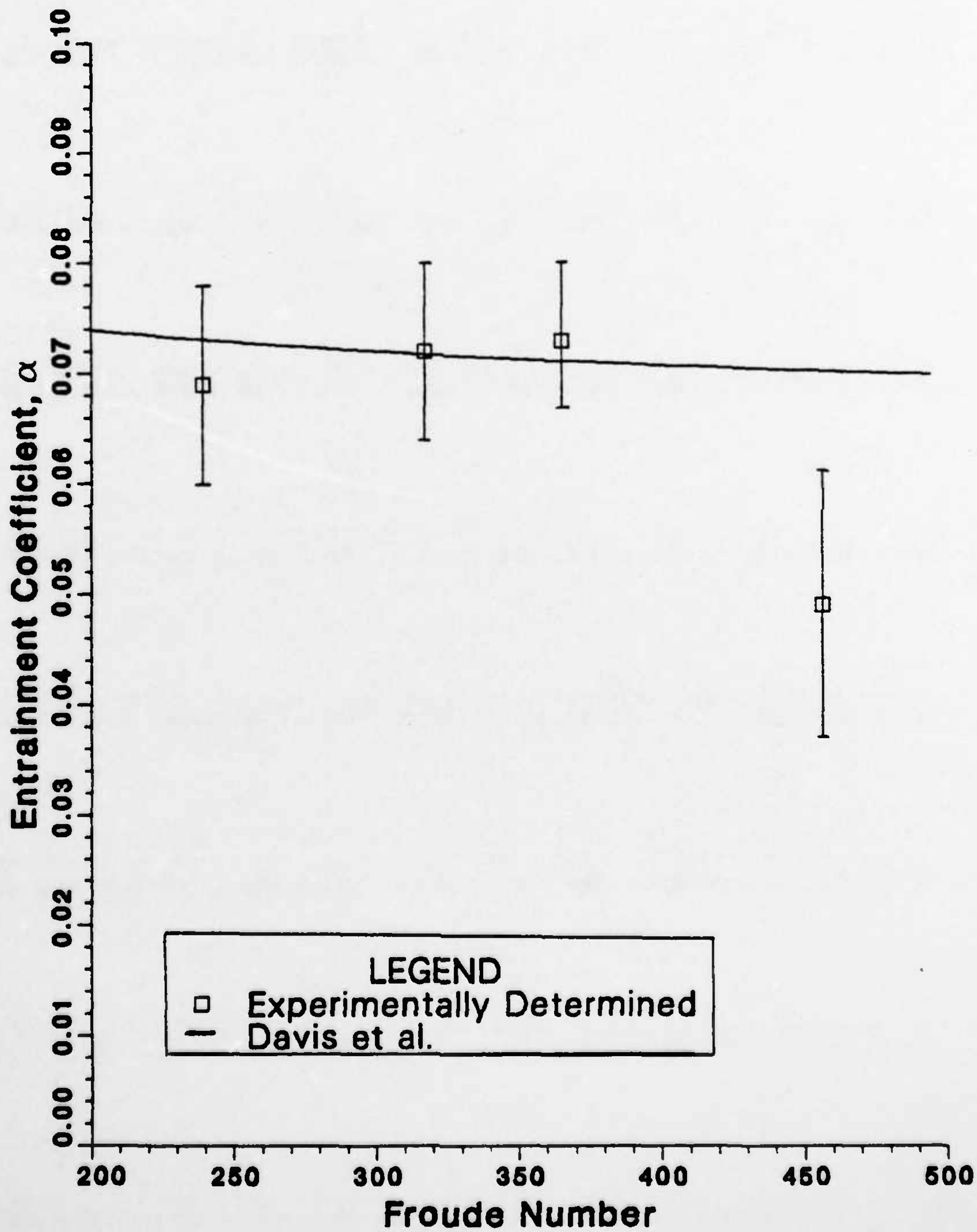
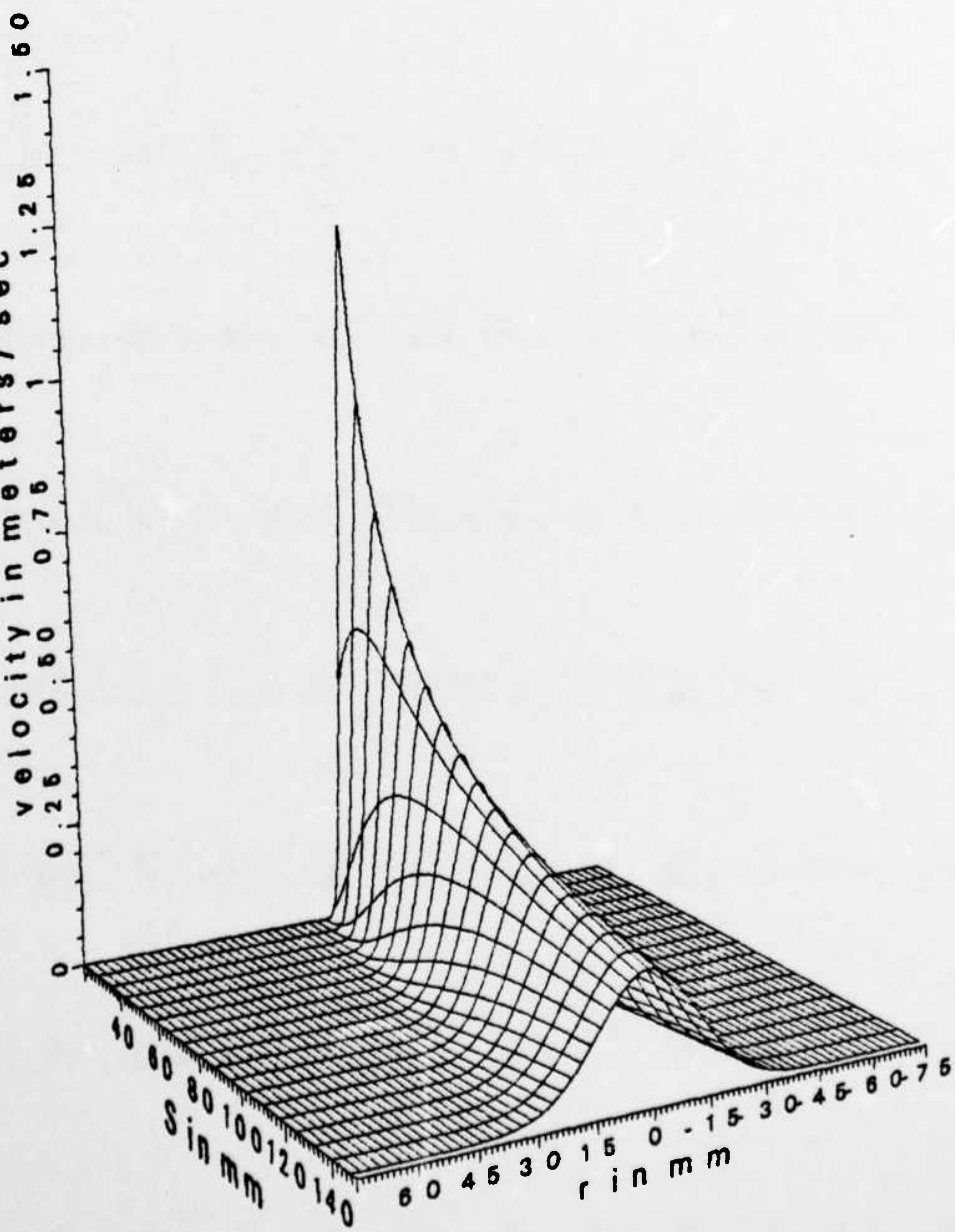


Fig 13. Streamwise

Jet Velocity Distribution



APPENDIX D.

COMPUTER PROGRAMS

```
10    !  PROGRAM LDV_TEST13
20    !
30    DIM Lbit(16),Height(140),V_data(200),Info(14)
40    GOSUB Clear_display
50    !
60    ON ERROR GOSUB Fix_errors
70    PRINTER IS 1
80    !
90    !  I. CONSTANTS.
100   !
110   Points=100      ! NUMBER OF POINTS OF DATA PER
120                   ! DISK FILE.
130   Max_points=200   !MAXIMUM NUMBER OF POINTS
140                    !PER DISK FILE ALLOWED.
150   Freq_shift=2000
160   Wavelength=6.328E-5
170   Foc_length=121.4
180   Beam_sep=22
190   Height_min=10!  MINIMUM HEIGHT ALLOWABLE FOR
200                !  A SINGLE DATA POINT.
210   Min_x=0      !  SET UP THE MINIMUM AND MAX.
220   Min_y=10     !  PLOTTABLE FOR X,Y ON THE
230   Max_x=133    !  GRAPHICS SCREEN.
240   Max_y=100
250   Data_set$="NONE"
260   Dont_clear=0
270   BEEP
280   Conversion=Wavelength/(2.*Beam_sep/(2.*Foc_length))
290   PEN 1
300   Jj=1
310 !
320 !      BEGIN DATA ACQUISITION AND SPECTRUM
330 !                   DISPLAY.
340 !
350 Begin: !
360          GOSUB First_questions
370          GOSUB Setup_keys
```

```
380 New_set:  !
390            GOSUB Second_question
400            GOSUB Spectrum
410 GOTO New_set
420 !
430 !
440 !      SUBROUTINES.
450 !
460 !
470 Spectrum:     !
480               ! DISPLAY THE SPECTRUM.
490               !
500   !  1. DRAW THE FIGURE AND SHOW THE ZERO
510   !     SPECTRUM.
520   !
530      Points=1
540      Count=1
550      GOSUB New_screen
560      GOSUB Draw_spectrum
570   !
580   !  2.  BEGIN THE DATA ACQUISITION.
590   !
600 Again:     !
610            !
620     ENTER 12 USING "#,W";Y
630     GOSUB Convert
640     GOSUB Take_data
650     GOSUB Label_count
660     GOSUB Get_height
670     GOSUB Draw_point
680     !
690     !
700     IF Count=20 THEN
710          GOSUB Find_peak
720          Count=0
730     END IF
740     Count=Count+1
```

```
          Count=Count+1
750       Points=Points+1
760     GOTO Again
770 RETURN
780 !
790 !
800 !
810 Setup_keys: !
820             ! SET UP THE SPECIAL KEYS TO BE
830             ! USED AS INTERRUPTS.
840             !
850             ON KEY 0 LABEL "CLEAR" GOSUB New_screen
860             ON KEY 1 LABEL "WRITE" GOTO Write_file
870             ON KEY 3 LABEL "<----" GOSUB Move_left
880             ON KEY 4 LABEL "---->" GOSUB Move_right
890             ON KEY 7 LABEL "QUIT" GOSUB Quit
900             ON KEY 2 LABEL "ZERO" GOSUB Zero_counter
910             ON KEY 5 LABEL "CHECK" GOSUB Check_frequency
920             ON KEY 9 LABEL "FREQ" GOSUB Change_freq
930 RETURN
940 !
950 !
960 !
970 Zero_counter: !
980               ! ZERO THE COUNTER USED TO COUNT
990               ! THE NUMBER OF DATA POINTS TO
1000              ! BE PLACED ON DISK.
1010              !
1020              Points=1
1030              GOSUB New_screen
1040 RETURN
1050!
1060!
1070!
1080 Move_left:!
1090            ! MOVE THE SPECTRUM DISPLAY CURSOR
1100            ! ONE STEP TO THE LEFT.
1110            !
```

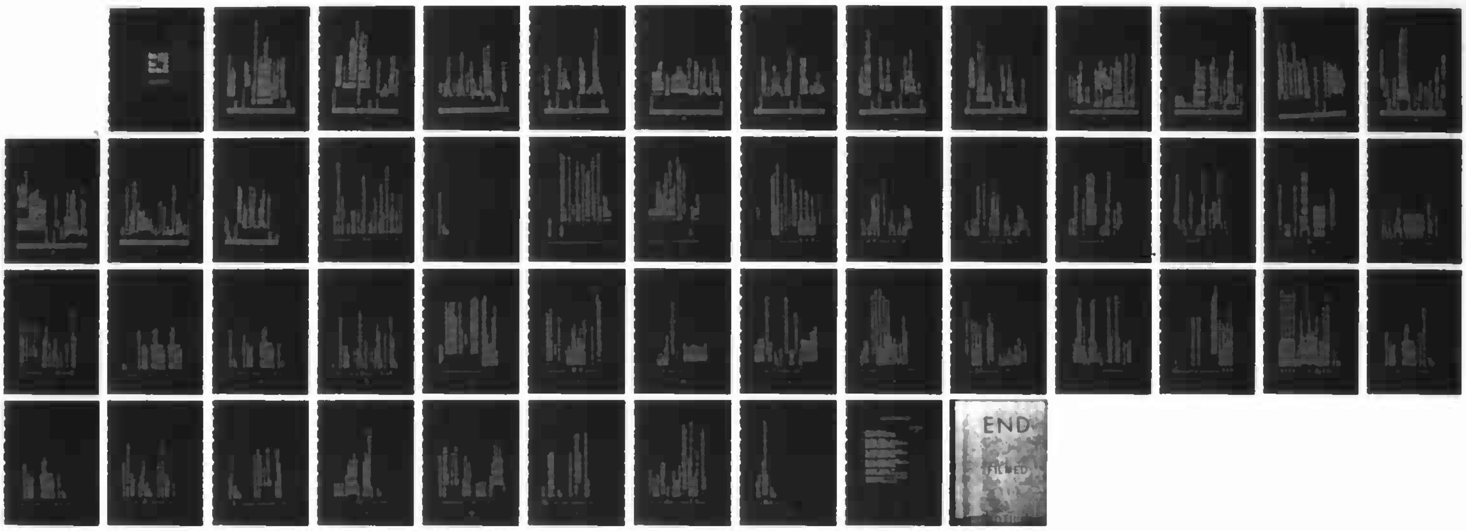
```
1120            I_choice=I_old-1
1130            IF I_choice>135 OR I_choice<0 THEN I_choice=0
1140            I_old=I_choice
1150            GOSUB Show_point
1160 RETURN
1170!
1180!
1190!
1200 Move_right:!
1210             ! MOVE THE SPECTRUM DISPLAY CURSOR
1220             ! ON STEP TO THE RIGHT.
1230             !
1240             I_choice=I_old+1
1250             IF I_choice>135 OR I_choice<0 THEN I_choice=0
1260             I_old=I_choice
1270             GOSUB Show_point
1280 RETURN
1290!
1300!
1310!
1320 Label_count:!
1330              ! LABEL THE NUMBER OF DATA POINTS
1340              ! COUNTED IN THE UPPER LEFT HAND
1350              ! CORNER OF THE GRAPH.
1360              !
1370              PRINT TABXY(1,1),"COUNT= ";Points
1380 RETURN
1390!
1400!
1410!
1420 Compute_blocks:!
1430                 ! COMPUTE THE NUMBER OF BLOCKS
1440                 ! PER DISK FILE.
1450                 !
1460      Blocks=INT((8*(Points+15))/256.0)+1
1470      BEEP
1480      GOSUB Clear_display
```

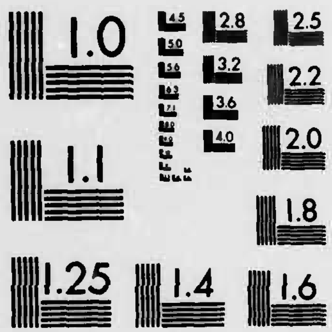
```
1480       GOSUB Clear_display
1490       PRINT "FOR ";Points;" POINTS OF DATA, ";Blocks;" BLOCKS PER DISK FILE
WILL BE ALLOTTED!"
1500       WAIT 2
1510       BEEP
1520 RETURN
1530 !
1540 !
1550 !
1560 Write_file: !
1570             ! WRITE ALL DATA POINTS INTO A
1580             ! FILE NAMED "NAME$".
1590             !
1600             IF Array_full=0 THEN
1610                PRINT "ARRAY NOT FULL YET!"
1620                BEEP
1630                BEEP
1640                RETURN
1650             END IF
1660             GOSUB Open_file
1670             GOSUB Clear_display
1680                BEEP
1690             Info(1)=VAL(Experiment$)
1700             Info(2)=VAL(Data_set$)
1710             Info(3)=Month
1720             Info(4)=Day
1730             Info(5)=Year
1740             Info(6)=(X_new-X_ref)*.0254
1750             Info(7)=(Y_new-Y_ref)*.0254
1760             Info(8)=(Z_new-Z_ref)*.0254
1770             Info(9)=T_nozzle
1780             Info(10)=T_ambient
1790             Info(11)=Nozzle_diam*25.4
1800             Info(12)=Flowmeter
1810             Info(13)=Orientation
1820             FOR I=1 TO 13
1830                OUTPUT @File;Info(I)
```

```
1840         PRINT "INFO(";I;") = ";Info(I)
1850      NEXT I
1860      !
1870      FOR I=1 TO Points
1880         OUTPUT @File;V_data(I)
1890         PRINT "DATA(";I;") = ";V_data(I)
1900      NEXT I
1910      Terminator=-200.0
1920      OUTPUT @File;Terminator
1930      PRINT "DATA(";Points+1;") = ";Terminator
1940      Array_full=0
1950      ASSIGN @File TO *
1960      PRINT "File <";Name$;"> created and written!"
1970      WAIT 2
1980 GOTO New_set
1990!
2000!
2010!
2020 Take_data:!
2030          ! TAKE VELOCITY DATA INTO A 100
2040          ! POINT ARRAY.
2050          !
2060          V_data(Jj)=Velocity
2070          Jj=Jj+1
2080          IF Jj>Points OR Jj>Max_points THEN
2090             Array_full=1
2100             Jj=1
2110          END IF
2120 RETURN
2130!
2140!
2150!
2160 Open_file:!
2170          ! 1. CREATE A FILE NAME.
2180          ! 2. CREATE THE DATA FILE.
2190          ! 3. OPEN THE FILE.
2200          !
```

AD-A132 316 MEASUREMENT OF VELOCITY DISTRIBUTIONS IN TURBULENT JETS USING A LASER DOPPLER VELOCIMETER(U) NAVAL POSTGRADUATE SCHOOL MONTEREY CA M D WESSMAN JUN 83 2/2

UNCLASSIFIED F/G 20/4 NL





MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

```
2210             Name$=Experiment$&"_DATA_"&Data_set$
2220             GOSUB Compute_blocks
2230             CREATE BDAT Name$,Blocks
2240             ASSIGN @File TO Name$
2250 RETURN
2260!
2270!
2280!
2290 First_questions: !
2300                  ! SET UP THE PROGRAM BY
2310                  ! ASKING THE INITIAL
2320                  ! QUESTIONS.
2330                  !
2340    GOSUB Clear_display
2350    INPUT "X,Y,Z POSITION OF JET CENTERLINE AT NOZZLE (MILS)?",X_ref,Y_ref,Z
_ref
2360    INPUT "EXPERIMENT NUMBER?",Experiment$
2370    INPUT "NOZZLE DIAMETER (IN)?",Nozzle_diam
2380    INPUT "FLOWMETER READING?",Flowmeter
2390    INPUT "MONTH,DAY,YEAR (2 DIGITS EACH)?",Month,Day,Year
2400    INPUT "LOWEST VELOCITY TO BE MEASURED (CM/S)?",Velocity_low
2410    INPUT "HIGHEST VELOCITY?",Velocity_high
2420    INPUT "FREQUENCY SHIFT (HZ)?",Freq_shift
2430    GOSUB Clear_display
2440         Range=Velocity_high-Velocity_low
2450         Delta_v=Range/135.0
2460         I_zero=-135.0*Velocity_low/Range+1
2470         !
2480         ! I_ZERO REPRESENTS THE HORIZONTAL
2490         ! POSITION AT WHICH THE VELOCITY IS
2500         ! ZERO.
2510         !
2520 RETURN
2530 !
2540 !
2550 !
```

```
2560 Second_question: !
2570                  ! ASK THE LDV POSITION, THE
2580                  ! DATA SET NUMBER AND THE
2590                  ! NUMBER OF CYCLES PER BURST.
2600                  !
2610                  GOSUB Clear_display
2620                  BEEP
2630                  BEEP
2640                  INPUT "T(C) AT THE NOZZLE BASE?",T_nozzle
2650                  INPUT "T(C) OF THE AMBIENT FLUID?",T_ambient
2660                  PRINT "MOVE THE LDV TO THE NEW POSITION."
2670                  INPUT "X,Y,Z POSITION OF THE LDV (MILS)?",X_new,Y_new,Z_ne
w
2680    INPUT "ORIENTATION (DEGREES) (0=HOR,90=VERT)?",Orientation
2690                  PRINT "PREVIOUS DATA SET NUMBER WAS: ";Data_set$
2700                  INPUT "DATA SET NUMBER?",Data_set$
2710                  INPUT "CYCLES PER BURST (POWER OF 2)?",Cycles
2720                  Cycles=2↑Cycles
2730                  GOSUB Clear_display
2740 RETURN
2750 !
2760 !
2770 !
2780 Convert:   !  CONVERT LDV VALUE TO VELOCITY
2790            !
2800            Low=1
2810            High=0
2820            Junk=ABS(Y)
2830            Ii=15
2840               Lbit(Ii)=Low
2850               IF Junk>2↑Ii THEN Lbit(Ii)=High
2860               IF Junk>2↑Ii THEN Junk=Junk-2↑Ii
2870               Ii=Ii-1
2880            IF Ii>-1 THEN GOTO 2840
```

```
2890              !
2900              !  MANTISSA
2910              !
2920              Mantissa=0
2930              FOR I=0 TO 11
2940                 Mantissa=Mantissa+(2↑I)*Lbit(I)
2950              NEXT I
2960              !
2970              !  EXPONENT
2980              !
2990              Exponent=0
3000              FOR I=12 TO 15
3010                 Exponent=Exponent+2↑(I-12)*Lbit(I)
3020              NEXT I
3030              !
3040              !  COMPUTE VELOCITY
3050              !
3060              Result=Mantissa*2↑(Exponent-3)
3070           IF Result=0. THEN
3080              Velocity=0
3090              BEEP
3100              BEEP
3110              DISP "BAD POINT!!"
3120           ELSE
3130              Frequency=Cycles*1.0E+9/Result-Freq_shift
3140              Velocity=Frequency*Conversion
3150              DISP "   V(CM/S)=";Velocity;"FREQ=";Frequency
3160              BEEP ABS(Velocity*10),.1
3170           END IF
3180         RETURN
3190!
3200!
3210!
3220 Draw_point:!
3230               ! CHANGE ONE CHANNEL ON THE
3240               ! SPECTRUM.
3250               !
```

```
3260             MOVE I_data,Height(I_data)
3270             LABEL "."
3280 RETURN
3290!
3300!
3310!
3320 Draw_spectrum:   !
3330                  !DRAW THE VELOCITY SPECTRUM.
3340                  !
3350                  FOR I=0 TO 135
3360                    MOVE I,Height(I)
3370                    LABEL "."
3380                  NEXT I
3390 RETURN
3400 !
3410 !
3420 !
3430 Get_height: !
3440              !GET THE HEIGHT ON THE SPECTRUM
3450              !CURVE CORRESPONDING TO ONE
3460              !VELOCITY DATA POINT.
3470              !
3480              I=0
3490              REPEAT
3500                I=I+1
3510              UNTIL Velocity<I*Delta_v+Velocity_low
3520              IF Velocity>Velocity_low AND Velocity<Velocity_high THEN
3530                Height(I)=Height(I)+1
3540                I_data=I
3550              END IF
3560 RETURN
3570 !
3580 !
3590 !
```

```
3600 New_screen: !
3610              !1. CLEAR THE SCREEN.
3620              !2. PUT ON THE AXES.
3630              !3. PUT ON THE LABELS.
3640              !4. ZERO THE HEIGHT() ARRAY.
3650              !5. DISPLAY THE LINE FOR ZERO
3660              !   VELOCITY.
3670              !
3680              GOSUB Clear_display
3690              MOVE Min_x,Min_y
3700              !
3710                DRAW Max_x,Min_y
3720                DRAW Max_x,Max_y
3730                DRAW Max_x-.5,Max_y
3740                DRAW Max_x-.5,Min_y+.5
3750                DRAW Min_x+.5,Min_y+.5
3760                DRAW Min_x+.5,Max_y
3770                DRAW Min_x,Max_y
3780                DRAW Min_x,Min_y
3790                MOVE 25,95
3800              LABEL "   LDV VELOCITY SPECTRUM"
3810              LABEL " "
3820              LABEL "<";
3830              LABEL USING "#,DD.DDD";Delta_v
3840              LABEL " (CM/S) PER CHANNEL>"
3850              !
3860              IF Dont_clear=0 THEN
3870                FOR I=0 TO 135
3880                  Height(I)=Height_min
3890                NEXT I
3900              END IF
3910              GOSUB Draw_spectrum
3920              !
3930              IF I_zero>0 AND I_zero<135 THEN
3940                 MOVE I_zero,Min_y
3950                 DRAW I_zero,Max_y/2
3960              END IF
3970 RETURN
```

```
3980 !
3990 !
4000 !
4010 Find_peak: !
4020            !1. FIND THE PEAK IN THE VELOCITY.
4030            !2. CALL "SHOW_POINT".
4040            !
4050            H_max=0
4060            !
4070            FOR I=0 TO 135
4080              IF Height(I)>H_max THEN
4090                I_max=I
4100                H_max=Height(I)
4110              END IF
4120            NEXT I
4130            !
4140            I_choice=I_max
4150            GOSUB Show_point
4160            IF Height(I_max)>80 THEN GOSUB New_screen
4170 RETURN
4180 !
4190 !
4200 !
4210 Show_point: !
4220             !FOR THE POINT "I_CHOICE", DISP-
4230             !LAY THE VELOCITY AND FREQUENCY.
4240             !SHOW THE POINT ON THE SPECTRUM
4250             !WITH A CROSS.
4260             !
4270               PEN 0
4280             MOVE X,Y
4290               LABEL "↑"
4300             X=I_choice
4310             Y=Height(I_choice)
4320             MOVE X,Y
4330               LABEL "↑"
4340               PEN 1
```

```
4350                  Keep_i=I_choice
4360                  Keep_h=Height(I_choice)
4370                MOVE 25,85
4380                Vel=I_choice*Delta_v+Velocity_low
4390                PRINT TABXY(8,6),"<VELOCITY = ";Vel;" (CM/S).>"
4400                PRINT TABXY(8,7),"<FREQUENCY = ";Vel/Conversion;" (HZ).>"
4410 RETURN
4420 !
4430 !
4440 !
4450 Clear_display: !
4460                   ! CLEAR THE ALPHA AND GRAPHICS
4470                   ! DISPLAYS.
4480                   !
4490                   GRAPHICS ON
4500                   OUTPUT 2 USING "#,B";255,75
4510                   GCLEAR
4520 RETURN
4530 !
4540 !
4550 !
4560 Fix_errors: !
4570                ! FIX ERRORS.
4580                !
4590                IF ERRN=31 THEN PRINT "DIVIDE/0"
4600                IF ERRN=54 THEN
4610                  GOSUB Clear_display
4620                  PRINT "I AM PURGING FILE <",Name$,">."
4630                  PURGE Name$
4640                END IF
4650                !
4660                OFF ERROR
4670 RETURN
4680 !
4690 !
```

```
4690 !
4700 !
4710 Check_frequency: !
4720                  ! FOR A GIVEN VELOCITY,
4730                  ! DISPLAY THE CORRESPONDING
4740                  ! FREQUENCY FOR THE LDV.
4750                  !
4760      GOSUB Clear_display
4770      INPUT "VELOCITY TO BE CONVERTED TO FREQUENCY (CM/S)?",V
4780      Frequency=V/Conversion
4790      PRINT "CORRESPONDING FREQUENCY (HZ) = ";Frequency
4800      PAUSE
4810      Dont_clear=1
4820      GOSUB New_screen
4830      Dont_clear=0
4840 RETURN
4850 !
4860 !
4870 !
4880 Change_freq: !
4890              ! CHANGE THE FREQUENCY OF THE
4900              ! BRAGG CELLS.
4910              !
4920      GOSUB Clear_display
4930      INPUT "NEW SHIFT FREQUENCY?",Freq_shift
4940      GOSUB New_screen
4950 RETURN
4960 !
4970 !
4980 !
4990 Quit: !
5000      GOSUB Clear_display
5010 END
```

```
10    !        PROGRAM "SEND_DATA"
20    !
30    !     To VAX,IBM,TRS-80.
40    !
50    !   HP-9826 TERMINAL PROGRAM
60    !   [REQUIRES BINARY ENHANCEMENT PROGRAM
70    !    "BEB"!]
80    !
90    !   JUNE 30, 1982
100   !   updated 1/5/83
110   !
120   !
130   !
140   Sc=9    ! RS-232 IS SELECT CODE 9.
150   PRINTER IS 1  ! PRINTER IS CRT.
160   Pr=1          ! DEFAULT PRINTER IS CRT
170   Printer_choice=12 ! MY PRINTER IS ON THE
180                 ! GPIO INTERFACE.
190   Bits=7        ! BITS PER CHARACTER
200   Duplex=0      ! FULL DUPLEX
210   Baud=300      ! BAUD RATE
220   Computer=1    ! ASSUME VAX COMPUTER
230   !
240   OUTPUT Pr;"ff300 BAUD, IBM assumed."
250   OUTPUT Pr;" Load the binary program BEB first"
260   OUTPUT Pr;" unless you have BASIC 2.0"
270   OUTPUT Pr;" SET MODEM ON <FULL DUPLEX> →"
280   OUTPUT Pr;" "
290   !
300   DIM Name$[200],Hp_file$[30],Aa(1500),Numb$[30]
310   INTEGER Isend
320   !
330   CONTROL Sc,3;Baud
340   CONTROL Sc,4;Bits-5+4 ! BITS/CHAR & #STOP BITS.
350   !
360   !
```

```
370   To_disk=0
380   Datadump=0
390   I_data=1
400   Data_set=0
410   Ldv$="n"
420   I=1
430   J=1
440   K=1
450   L=1
460   !
470   ON ERROR GOTO Errors
480   ON KEY 0 LABEL "Line Mode" GOTO Line_mode
490   ON KEY 5 LABEL "Terminal" GOTO Terminal
500   ON KEY 6 LABEL "To Crt" GOTO Pr_crt
510   ON KEY 7 LABEL "To Prt" GOTO Pr_prt
520   ON KEY 8 LABEL "DATA" GOTO Data_dump
530   !
540   !
550 Line_mode:    !
560        OUTPUT Pr;"πLINE RECEPTION MODE→"
570 Begin: STATUS Sc,10;Y ! CHECK FOR FULL BUFFER
580        ON KBD GOTO Transmit
590        IF BIT(Y,0)=0 THEN GOTO Begin
600   !
610   !  RECEIVE ROUTINE.
620   !
630 Receive:     STATUS Sc,6;A
640      B=A
650      OUTPUT Pr USING "#,A";CHR$(B)
660      IF B=63 AND Datadump=1 THEN GOTO Data_dump
670      IF B=13 AND Computer=3 THEN OUTPUT Pr;CHR$(13)
680      GOTO Begin
690   !
700   !  TRANSMIT ROUTINE.
710   !
720 Transmit:    Key$=KBD$
```

```
730                IF Duplex=0 THEN
740                   IF NUM(Key$)<>255 THEN OUTPUT Pr USING "#,A";Key$
750                   IF NUM(Key$)=255 THEN OUTPUT Pr;" "
760                END IF
770                IF Computer=1 AND NUM(Key$)=8 THEN Key$=CHR$(64)
780                !
790                !  the previous line gives an @
800                !  for a backspace for the IBM.
810                !
820                IF Computer=5 AND NUM(Key$)=8 THEN Key$=CHR$(127)
830                !
840                !  THE VAX/VMS REQUIRES A DELETE
850                !  SYMBOL FOR A BACKSPACE.
860                !
870                IF NUM(Key$)=255 THEN Key$=CHR$(13)
880                OUTPUT Sc USING "#,A";Key$
890                GOTO Begin
900   !
910   !
920   !
930   !    DATA FILE OUT TO THE HOST COMPUTER.
940   !
950   !
960   !
970 Data_dump:     !
980                IF I_data=1 THEN GOSUB Open_file
990                !
1000               IF Datadump=0 THEN GOTO Begin
1010                  IF Computer=1 THEN WAIT .3
1020                  ! wait for the slow IBM.
1030                  BEEP 1000+RND*1500,.05
1040                  OUTPUT Pr;"A(";I_data;")=";
1050                  OUTPUT Pr;Aa(I_data)
1060                  GOSUB Send_number
1070               IF Aa(I_data)=-200 THEN
1080                     I_data=1
```

```
1090                    IF (Ldv$="1") THEN GOSUB Data_dump
1100                    Datadump=0
1110             END IF
1120             I_data=I_data+1
1130 GOTO Begin
1140 !
1150 !
1160 !  ERROR HANDLING SUBROUTINE
1170 !
1180 Errors:  OFF ERROR
1190          IF ERRN<>59 THEN OUTPUT Pr;"<error #";ERRN;" generated.>"
1200          IF ERRN=54 THEN OUTPUT Pr;"πFILE <";Hp_file$;"> ALREADY THERE→"
1210          IF ERRN=54 THEN GOTO Created
1220          IF ERRN=56 THEN OUTPUT Pr;"<FILE <";Hp_file$;" IS NOT ON DISK.>"
1230          ASSIGN @File TO *
1240 GOTO Line_mode
1250 !
1260 !
1270 !  OUTPUT TO CRT.
1280 !
1290 Pr_crt:  Pr=1
1300          GOTO Line_mode
1310 !
1320 !
1330 !  OUTPUT TO PRINTER.
1340 !
1350 Pr_prt:  Pr=Printer_choice
1360 GOTO Line_mode
1370 !
1380 !
1390 !  CHANGE THE TERMINAL CHARACTERISTICS.
1400 !
1410 Terminal:  !
1420            OUTPUT Pr;"     1.  Baud Rate =";Baud
1430            OUTPUT Pr;"     2.  Bits/Char =";Bits
```

```
1440            OUTPUT Pr;"     3.  Duplex    =";Duplex
1450            OUTPUT Pr;"         [1=full,0=half]"
1460            OUTPUT Pr;"     4.  Computer  =";Computer
1470            OUTPUT Pr;"         [IBM=1, VAX/UNIX=2, "
1480            OUTPUT Pr;"          TRS-80=3, Cyber=4, vax/vms=5]"
1490            OUTPUT Pr;" "
1500            INPUT "Change which one?",Which
1510            IF Which=1 THEN INPUT "To?",Baud
1520            IF Which=2 THEN INPUT "To?",Bits
1530            IF Which=3 THEN INPUT "To?",Duplex
1540            IF Which=4 THEN INPUT "To?",Computer
1550            IF Computer=1 THEN Duplex=0
1560            IF Computer=3 THEN Duplex=0
1570            IF Computer=3 THEN Bits=8
1580            IF Computer=5 THEN Duplex=1
1590 GOTO Line_mode
1600 !
1610 !
1620 !
1630 Open_file:  !
1640             !  Open a file to read data from
1650             !  disk.
1660             !
1670     Datadump=1
1680     !
1690     IF Data_set=0 THEN
1700       INPUT "Is this LDV data? <1=YES>",Ldv$
1710       IF Ldv$="1" THEN
1720         INPUT "Experiment #?",Experiment$
1730         INPUT "Beginning data set #?",Begin_set
1740         INPUT "Last data set #?",Last_set
1750         Data_set=Begin_set-1
1760         Ldv$="1"
1770       ELSE
1780         OUTPUT Pr;"Data file out of HP to host."
1790         INPUT "File name?",Hp_file$
1800       END IF
```

```
1810       !
1820     END IF
1830     !
1840     !  For LDV data after the first data set.
1850     !
1860     IF Ldv$="1" THEN
1870       Data_set=Data_set+1
1880       Hp_file$=Experiment$&"_DATA_"&VAL$(Data_set)
1890       !
1900       IF Data_set>Last_set THEN
1910         OUTPUT Pr;"-500"
1920         Aa(I_data)=-500
1930         GOSUB Send_number
1940         Datadump=0
1950         Check=-500
1960         I_data=1
1970         GOTO Begin
1980       END IF
1990       !
2000     END IF
2010     !
2020     !  Read the file off of disk.
2030     !
2040     ASSIGN @File TO Hp_file$
2050     I=1
2060     Check=0
2070     BEEP
2080     BEEP
2090     OUTPUT Pr;"πWorking on file <";Hp_file$;">.→"
2100     !
2110     WHILE Check<>-200
2120       ENTER @File;Aa(I)
2130       Check=Aa(I)
2140       I=I+1
2150     END WHILE
2160     !
2170     ASSIGN @File TO *
```

```
2180        Datadump=1
2190 RETURN
2200 !
2210 !
2220 !
2230 Send_number: !
2240                 ! SEND A NUMBER ONE CHARACTER AT
2250                 ! A TIME TO THE HOST COMPUTER.
2260                 !
2270          Numb$=VAL$(Aa(I_data))
2280          Length=LEN(Numb$)
2290          !
2300          IF ((Ldv$="1") AND (I_data>13)) THEN
2310            Posit=POS(Numb$,".")
2320            IF (Posit<>0) THEN Length=Posit+2
2330          END IF
2340          !
2350          FOR I=1 TO Length
2360            Numeric=NUM(Numb$[I,I])
2370            OUTPUT Sc USING "#,A";Numb$[I,I]
2380          NEXT I
2390          !
2400          OUTPUT Sc USING "#,A";CHR$(13)
2410 RETURN
2420 !
2430 !
2440 !
2450 END
```

```
c
c      Program Ldvgrab
c
c      PURPOSE:  Transfer data from the HP-9826 computer to the VAX.
c
c      channel 1 -- disk file 'ldvdata'.
c
c
c      12/31/82
c
       dimension data(3000)
       character*8  myfile
c
       myfile = 'ldvdata'
       i=1
       write(6,80)
80     format(2x,'Begin inputting data from the HP-9826.')
c
c
10     continue
       read(5,*) data(i)
       i=i+1
       if(data(i-1).ne.-200) go to 10
c
       nitems=i-1
6      format(2x,i5,'  data points were entered.')
       write(6,6) nitems
c
c      Now that all data has been entered, write it out on disk.
c
       open(1,file=myfile)
5      format(2x,'data(',i5,') = ',1f15.5)
       i=1
20     write(1,*) data(i)
       i=i+1
       if(data(i-1).ne.-200) go to 20
```

```
c
c     All data has been written onto disk.
c
      close(1)
      stop
      end
```

```
C
C
C
C     PROGRAM LDVMEAN
C
C
C
C
C
C     PURPOSE: 1.  Compute the mean velocities and Reynolds stresses from LDV
C                  data on disk.  Incorporate Chauvenet's Criterion in data
C                  validation.
C
C              2.  Read raw LDV data off of the disk from files of the name:
C
C                       "dXXXYYY"
C
C                  where "XXX" represents the experiment number and "YYY" the
C                  data set number.
C
C              3.  Assume that the data files are formed as follows:
C
C                  a.  odd data sets -- vertical orientation.
C                  b.  even data sets-- horizontal orientation.
C
C                       Data sets #1, #2 are both taken with the LDV at the
C                  same position, and so on.
C
C              4.  Write out the following information onto disk for each pair
C                  of data sets.
C
C                  a.  experiment number.
C                  b.  data set number.
C                  c.  month.
C                  d.  day.
```

```
c                  e.  year.
c                  f.  x(mm).
c                  g.  y(mm).
c                  h.  z(mm).
c                  i.  Nozzle temperature (C).
c                  j.  Ambient fluid temperature (C).
c                  k.  Nozzle diameter (mm).
c                  l.  Flowmeter reading.
c                  m.  Orientation (vertical = 90)
c                  n.  mean u (cm/s) -- streamwise velocity.
c                  o.  mean v (cm/s).
c                  p.  mean u'**2/(mean u)**2  -- Turbulence intensity.
c                  q.  mean v'**2/(mean v)**2 .
c                  r.  mean u'v'/(mean u)*(mean v).
c
c                  This is repeated for each pair of readings!  A "-200" is
c                  used as a file terminator.  The file is called:
c
c                       "meanXXX"      ,"XXX" = experiment #.
c
c
c      CALL:
c              1.  Subroutines:
c                  a.  fname
c                  b.  fname1
c                  c.  fname2 (optional)
```

d. statis

```
c
c
c
c
c
c
      integer iset,setmin,setmax,iexp,litems,iptsu,iptsv
      dimension udata(300),vdata(300),expout(500),dinfo(14)
      character*11 kname1,kname
      real umean,vmean,usdev,vsdev,sum1,sum2,sum3,u2bar,v2bar,uvbar
c
c     1.  Read the data from disk.
c
c         a.  The pair of files to be read are of the form:
c
c             "dXXXYYY"
c
c             where "XXX" is the experiment number and
c             "YYY" is the data set number.
c
      write(6,100)
100   format(2x,'Input the experiment number.')
      read(5,*) iexp
      write(6,101)
101   format(2x,'Beginning data set number?')
      read(5,*) setmin
      write(6,102)
102   format(2x,'Last data set number?')
      read(5,*) setmax
c
c
c          b.  Form the vertical file name:
c
c
```

```
      iset = setmin - 1
      iout = 0
c
10    continue
      iset = iset + 1
           call fname(iset,iexp,kname)
103   format(2x,'Accessing VERTICAL file: ',A11)
           write(6,103) kname
      open(unit=1,file=kname,status='old')
c
c
c          c.  Read the contents of the vertical file.
c
c
      do 97 k=1,13
           read(1,*) dinfo(k)
97    continue
c
      i = 1
      check = 0.0
c
11    continue
      if(check .ne. -200.0) then
           read(1,*) udata(i)
             check = udata(i)
           i = i + 1
```

```
          go to 11
        end if
c
        close(unit=1)
        nitems = i - 2
        iptsu = nitems
        call statis(udata,nitems,iptsu,umean,usdev)
c
c
c             d.  Now, read the file for horizontal data.
c
c
        iset = iset + 1
             call fname(iset,iexp,kname)
113     format(2x,'      and the HORIZONTAL file:   ',A11)
             write(6,113) kname
        open(unit=1,file=kname,status='old')
c
c
c
        do 901 k=1,13
             read(1,*) junk
901     continue
c
        i=1
        check = 0.0
13      continue
        if(check .ne. -200.0) then
             read(1,*) vdata(i)
             check = vdata(i)
             i = i + 1
             go to 13
        end if
c
```

```
      close(unit=1)
      litems = i - 2
      iotsv = litems
      call statis(vdata,litems,iptsv,vmean,vsdev)
c
c
c
c     2.  Apply Chauvenet's Criterion.
c
c         a.  If the deviation for a particular data point
c             "dev" exceeds that value allowed by Chauve-
c             net's Criterion given by "devmax", then throw
c             that point away and recompute the mean and
c             standard deviation.
c
c
      i = 0
12    continue
      i = i + 1
      dev = abs(udata(i) - umean)
      devmax = usdev * (1.05389 + 0.36749*log(float(nitems)))
c
c
      if(i .le. nitems) then
c
          if(dev .gt. devmax) then
              udata(i) = -999.9
```

```
                  iptsu = iptsu - 1
                  call statis(udata,nitems,iptsu,umean,usdev)
              end if
c
              go to 12
          end if
c
c
c             b.  Repeat for the horizontal file.
c
c
          i = 0
14        continue
          i = i + 1
          dev = abs(vdata(i) - vmean)
          devmax = vsdev * (1.05389 + 0.36749*log(float(litems)))
c
c
          if(i .le. litems) then
c
              if(dev .gt. devmax) then
                  vdata(i) = -999.9
                  iptsv = iptsv - 1
                  call statis(vdata,litems,iptsv,vmean,vsdev)
              end if
c
              go to 14
          end if
c
```

```
c
c         b.  Compute the turbulence intensities.
c
c
      sum1 = 0.0
      sum2 = 0.0
      sum3 = 0.0
c
c
      if(litems .lt. nitems) then nitems = litems
c
c
      do 900 i=1,nitems
           sum1 = sum1 + (umean - udata(i))*(umean - udata(i))
           sum2 = sum2 + (vmean - vdata(i))*(vmean - vdata(i))
           sum3 = sum3 + (umean - udata(i))*(vmean - vdata(i))
900   continue
c
c
      u2bar = sum1/float(nitems)
      u2bar = u2bar/(umean*umean)
      v2bar = sum2/float(nitems)
      v2bar = v2bar/(vmean*vmean)
      uvbar = sum3/float(nitems)
      uvbar = uvbar/(umean*vmean)
c
c
c
c          c.  Store the experiment information
c              into an array, "expout(500)".
c
c
```

```
      if(iset .eq. setmin+1) then
           iout = 0
      else
           iout = iout - 1
      end if
c
      do 93 i=1,13
           iout = iout + 1
           expout(iout) = dinfo(i)
93    continue
c
           iout = iout + 1
      expout(iout) = umean
           iout = iout + 1
      expout(iout) = vmean
           iout = iout + 1
      expout(iout) = u2bar
           iout = iout + 1
      expout(iout) = v2bar
           iout = iout + 1
      expout(iout) = uvbar
           iout = iout + 1
c
c
c     3.  Repeat for all data sets in this
c         experiment.
c
c
      if(iset .lt. setmax) go to 10
c
```

```
c
c
c     4.  Write out the means and standard
c         deviations onto disk.
c
c          a.  Form a disk file of the form:
c
c              "expXXX"
c
c              where "XXX" is the experiment
c              number.
c
c
c
      call fname1(iexp,kname1)
      open(unit=1,file=kname1,status='new')
c
      expout(iout) = -200.0
c
      do 94 i=1,iout
           write(1,*) expout(i)
94    continue
c
      close(unit=1)
c
c
c     5.  End the program.
c
c
105   format(2x,'A total of ',i5,' data sets were done!')
      write(6,105) iset-setmin+1
```

```
      stop
      end
c
c
c
c
c
c
      subroutine fname(iset,iexp,kname)
c
      character*1 k1,k2,k3
      character*3 kset,kexp
      character*11 kname
c
c
      iset1 = int(iset/100)
      iset2 = int(iset/10) - iset1 * 10
      iset3 = iset - iset1*100 - iset2*10
      k1 = char(iset1 + 48)
      k2 = char(iset2 + 48)
      k3 = char(iset3 + 48)
      kset = k1//k2//k3
c
c
      iexp1 = int(iexp/100)
      iexp2 = int(iexp/10) - iexp1*10
      iexp3 = iexp - iexp1*100 - iexp2*10
      k1 = char(iexp1 + 48)
      k2 = char(iexp2 + 48)
      k3 = char(iexp3 + 48)
      kexp = k1//k2//k3
c
```

```
c
c
      kname = 'd'//kexp//kset//'.dat'
c
      return
      end
c
c
c
      subroutine fname1(iexp,kname)
c
      character*1 k1,k2,k3
      character*3 kexp
      character*11 kname
c
c
c
c
      iexp1 = int(iexp/100)
      iexp2 = int(iexp/10) - iexp1*10
      iexp3 = iexp - iexp1*100 - iexp2*10
      k1 = char(iexp1 + 48)
      k2 = char(iexp2 + 48)
      k3 = char(iexp3 + 48)
      kexp = k1//k2//k3
c
c
      kname = 'mean'//kexp
c
      return
```

```
      end
c
c
c
      subroutine statis(data,nitems,ipts,mean,sd)
c
      dimension data(300)
      integer nitems,ipts
      real mean,sd
c
c
           sum = 0.0
c
      do 95 i=1,nitems
           if(data(i) .ne. -999.9) sum = sum + data(i)
95    continue
c
      mean = sum/float(ipts)
c
c
           sum = 0.0
c
      do 96 i=1,nitems
           if(data(i) .ne. -999.9) sum = sum +
     1 (data(i)-mean)*(data(i)-mean)
96    continue
c
      sd = sqrt(sum/(float(ipts-1)))
c
c
107   format(2x,'Points,mean,s.dev. = ',i6,2f10.3)
      write(6,107) ipts,mean,sd
      return
      end
```

```
c        PROGRAM ENTRAIN
c          7 April 1083
c
c                This program reduces ldv data through fitting
c                velocity data to first a Gaussian curve
c                then the coefficients thus obtained to power
c                curves to obtain general expressions for the
c                velocity distributions in the jets.  Only the
c                axisymmetric case is considered.
c
c                The data file to be read from disk is stored
c                in files of the form:
c
c                          "meanXXX"
c
c
c                Output for report tabulation is stored in file
c                "entrn.dat".  All dimensions are normalized with
c                respect to the nozzle diameter and all velocities
c                with respect to the nozzle centerline velocity.
c
c
      dimension x(200),y(200),z(200),u(200),v(200),uprime(200),
     cvprime(200),reystrs(200),xtrace(200),ytrace(200),ztrace(200)
      real a1,a2,b1,b2,regu,regb
      real k1(10),k2(10)
      character*11  kname
      integer data, orien,count,l,mo,da,yr,iexp
      real tn,ta,suntn,sumta,tmn,tma,b,um,fm,q,re,vis,ro
      common idiagn
c
```

```
c
c
c     1.  To read in LDV data, form the name of the
c         disk file containing velocity means and
c         turbulence levels.  The file is of the form:
c
c             "meanXXX"
c
c         where "XXX" is the experiment number.
c
c
c
      write(6,100)
      read(5,*) idiagn
      write(6,101)
101   format(2x,'Experiment number?')
100   format(2x,'Diagnostics? (0=none):')
      read(5,*) iexp
      call fname2(iexp,kname)
102   format(2x,'Opening file: ',A11)
      write(6,102) kname
      open(unit=1, file=kname, status='old')
c
c
c
c     2.  Read in the data off of disk.
c
c
c        a.  Store x,y,z,u,v,uprime,vprime,and reystrs in separate arrays
c        b.  "x" represents the radial component of position.
```

```
c
c
c
      i = 0
      sumtn = 0
      sumta = 0
10    continue
      read(1,*) nexp
      if(nexp .ne. -200.0) then
c
c
c              Increment the counter if data is to be read.
c
         i = i + 1
c
c
c
         read(1,*) data
         read(1,*) mo
         read(1,*) da
         read(1,*) yr
         read(1,*) x(i)
         read(1,*) y(i)
         read(1,*) z(i)
         read(1,*) tn
         read(1,*) ta
         read(1,*) d
         read(1,*) fm
         read(1,*) orien
```

```
         read(1,*) u(i)
         read(1,*) v(i)
         read(1,*) uprime(i)
         read(1,*) vprime(i)
         read(1,*) reystrs(i)
c
c              Compute a running total of the temperature values.
         sumtn = sumtn+tn
         sumta = sumta+ta
c
         go to 10
      end if
c
      close(unit=1)
c
c
c               Compute the mean temperatures for the experiment.
c
      tma = sumta/i
      tmn = sumtn/i
c
c               Place all measurements in SI units.
c
      do 12 ii = 1,i
         x(ii) = x(ii)/1000
         y(ii) = y(ii)/1000
         z(ii) = z(ii)/1000
         u(ii) = u(ii)/100
         v(ii) = v(ii)/100
         uprime(ii)=uprime(ii)/100
         vprime(ii)=vprime(ii)/100
         reystrs(ii)=reystrs(ii)/10000
```

```
12    continue
        d = d/1000
        tma = (tma-32)*5/9
        tmn = (tmn-32)*5/9
c
c
c              Compute properties and Reynolds Number at jet exit.
c
       vis=(1.715-.04845*tmn+.00076462*tmn**2-.6284e-5*tmn**3+.20516e-7
      c*tmn**4)*1.0e-3
       ro=(1.0000+.3519e-4*tmn-.6956e-5*tmn**2+.3412e-7*tmn**3-.9741e-10
      c*tmn**4)*1000
       roamb=(1.0000+.3519e-4*tma-.6956e-5*tma**2+.3412e-7*tma**3
      c-.9741e-10*tma**4)*1000
       q = (-.61793+.48557*fm-.00270*fm**2+.00003*fm**3)/1.0e6
       umn = q/(3.14159*d**2/4)
       re = umn*d*ro/vis
       if (re .ge. 2300) then
         umax = umn/.817
       else
         umax = umn/0.50
       end if
       fr = umax/sqrt(9.81*d*((roamb-ro)/roamb))
       alphao = .057+0.083/fr**0.3
c
c
c
c
c
```

```
c
c               Initialize file containing the error information.
c
c
      open (unit=4,file='error',status='new')
      write (4,200)
200   format (2x,'GAUSSIAN FIT INFORMATION')
      write (4,201) iexp
201   format (2x,'Experiment Number ',i4)
c
c
c
c     3.  Read values of velocity into
c         a one dimensional array.  Fit the array
c         according to a Gaussian Profile.
c
c
c
      itrace = 1
      k = 0
      count = 1
      l = 0
15    continue
      count = count + 1
      k = k + 1
      l = l + 1
      xtrace(k) = x(l)
      ytrace(k) = u(l)
      if (count .eq. i) then
        k = k + 1
        l = l + 1
        xtrace(k) = x(l)
```

```
        ytrace(k) = u(1)
        ztrace(itrace) = z(1)
        call gaufit(k,xtrace,ytrace,k1(itrace),k2(itrace))
        call error1(k,k1(itrace),k2(itrace),z(1),xtrace,ytrace)
        close (unit=4)
      else if (z(count) .eq. z(1)) then
        go to 15
      else
        ztrace(itrace) = z(1)
        call gaufit (k, xtrace,ytrace,k1(itrace),k2(itrace))
        call error1(k,k1(itrace),k2(itrace),z(1),xtrace,ytrace)
        itrace = itrace + 1
        k = 0
        go to 15
      end if
c
c
c
c       Now fit the centerline velocities and jet characteristic
c       widths to power curves.
c
c
c       Transform k1 and k2 values to centerline velocity and jet
c       characteristic width.
c
c
      do 20 j = 1,itrace
c
        k1(j)=exp(k1(j))
        k2(j)=sqrt(1/k2(j))
```

```
c
20    continue
c
c
c
c
c
c
c
c
      call powfit (itrace,ztrace,k1,a1,a2,regu)
c
c
      call powfit (itrace,ztrace,k2,b1,b2,regb)
c
c
c
c
c
c
c           Write out the tabular data to disk file, while
c           computing the quantities as dimensionless variables.
c           Also compute the mean value of the entrainment coefficient.
c
      open (unit=2,file='entrn',status='new')
      write (2,110)
110   format (2x,'PROGRAM ENTRAIN OUTPUT')
      write (2,111) iexp
111   format (//,2x,'EXPERIMENT NUMBER',i4)
      write (2,112) mo,da,yr
112   format (2x,'EXPERIMENT CONDUCTED',i2,'/',i2,'/',i2)
```

```
      write (2,113) tma,tmn
113   format (2x,'Ambient Temp, (C) ',f5.2,2x,'Nozzle Temp, (C) ',f5.2)
      write (2,114) a1,a2,regu
114   format (2x,'a1= ',f10.7,' a2= ',f10.7,' Coef of det.= ',f10.9)
      write (2,115) b1,b2,regb
115   format (2x,'b1= ',f10.7,' b2= ',f10.7,' Coef of det.= ',f10.9)
      write (2,116) re,fr,umax
116   format (2x,'Reynolds No. ',f10.2,2x,'Froude No. ',f10.2,2x,'Vel. ',
     cf10.8)
      alpham = 0.0
      do 40 i = 1,itrace
        alpha = ((2.0*b2+a2)*b1*ztrace(i)**(b2-1.0))/2.0
        alpham = alpham + alpha
        zbar = ztrace(i)/d
        write (2,117) zbar, alpha
117   format (//2x,'S/d  ',f10.5,2x,'Entrainment Coefficient ',f10.5)
        bbar = b1*ztrace(i)**b2/d
        ubar = a1*ztrace(i)**a2/umax
        write (2,118) bbar,ubar
118   format (2x,'b/d= ',f10.8,' Um/Umo= ',f10.8)
40    continue
      alpham = alpham/itrace
      write (2,119) alpham
119   format (2x,'Mean entrainment coefficient= ',f10.5)
      write (2,120) alphap
120   format (2x,'Expected maximum entrainment coefficient= ',f10.5)
c
c
      close (unit=2)
c
      stop
      end
```

```
c
c
c
      subroutine fname2(iexp,kname)
c
      character*1 k1,k2,k3
      character*3 kexp
      character*11 kname
c
c
c
c
      iexp1 = int(iexp/100)
      iexp2 = int(iexp/10) - iexp1*10
      iexp3 = iexp - iexp1*100 - iexp2*10
      k1 = char(iexp1 + 48)
      k2 = char(iexp2 + 48)
      k3 = char(iexp3 + 48)
      kexp = k1//k2//k3
c
c
      kname = 'mean'//kexp//'.dat'
c
c     Note:  the '.dat' is only necessary for VAX/VMS!!!
c
c
      return
      end
c
```

```
c
c
      subroutine fname3(iexp,kname)
c
      character*1 k1,k2,k3
      character*3 kexp
      character*11 kname
c
c
c
c
      iexp1 = int(iexp/100)
      iexp2 = int(iexp/10) - iexp1*10
      iexp3 = iexp - iexp1*100 - iexp2*10
      k1 = char(iexp1 + 48)
      k2 = char(iexp2 + 48)
      k3 = char(iexp3 + 48)
      kexp = k1//k2//k3
c
c
      kname = 'coef'//kexp
c
      return
      end
c
c
c
c
c
c
c
c
c
```

```
c
c
      real function amax(x,nitems)
c
c     PURPOSE:  Find the maximum value in an array.
c
      dimension x(nitems)
      integer nitems
c
c
      xmax = x(1)
      do 340 i=1,nitems
           if(x(i) .gt. xmax) xmax = x(i)
340   continue
      amax = xmax
      return
      end
c
c
c
      real function amin(x,nitems)
c
c     PURPOSE:  Find the minimum value in an array.
c
      dimension x(nitems)
      integer nitems
c
c
      xmin = x(1)
```

```
      do 340 i=1,nitems
           if(x(i) .lt. xmin) xmin = x(i)
340   continue
      amin = xmin
      return
      end
c
c
c
c
c
c
c
      subroutine powfit(nitems,z,x,A1,A2,r)
c
c     PURPOSE:  Fit the data "z(x)" according to
c               an power curve of the form:
c
c               z(x) = A1*x**A2
c
c               Return the coefficients "A1" and
c               "A2".
c
c
      integer nitems
      real A1,A2,sum1,sum2,sum3,sum4,sum5,denom,r
      dimension x(nitems),z(nitems)
c
c
c
```

```
c
      sum1 = 0.0
      sum2 = 0.0
      sum3 = 0.0
      sum4 = 0.0
      sum5 = 0.0
c
      do 950 i=1,nitems
         sum1 = sum1 + alog(z(i))
         sum2 = sum2 + (alog(z(i))**2)
         sum3 = sum3 + alog(x(i))
         sum4 = sum4 + alog(z(i))*alog(x(i))
         sum5 = sum5 + (alog(x(i))**2)
950   continue
c
c
      denom = nitems*sum2-sum1*sum1
      a1 = exp((sum3*sum2-sum4*sum1)/denom)
      a2 = (nitems*sum4-sum3*sum1)/denom
      r = (alog(a1)*sum3+a2*sum4-(sum3**2/nitems))/(sum5-sum3**2/
     cnitems)
c
c
      return
      end
c
c
c
c
c
c
```

```
c
      subroutine gaufit(nitems,x,z,k1,k2)
c
c     PURPOSE:  Fit the data "z(x)" according to
c               a Gaussian Normal Distribution of
c               the form:
c
c               z(x) = exp(k1 - k2 * x * x)
c
c               Return the coefficients "k1" and
c               "k2".
c
c
      integer nitems
      real k1,k2,sumx2,sums4,sumzx2,sumz
      real points
      dimension x(nitems),z(nitems)
c
c
c
      sumx2 = 0.0
      sumx4 = 0.0
      sumzx2 = 0.0
      sumz = 0.0
      points = 0.0
c
c
      do 950 i=1,nitems
         if (z(i) .gt. 0.0) then
            sumx2 = sumx2 + x(i)*x(i)
            sumx4 = sumx4 + x(i)*x(i)*x(i)*x(i)
            sumz = sumz + alog(z(i))
            sumzx2 = sumzx2 + alog(z(i))*x(i)*x(i)
            points = points + 1.0
         end if
```

```
950   continue
c
c
      denom = points * sumx4 - sumx2*sumx2
      k1 = (sumz*sumx4 - sumzx2*sumx2)/denom
      k2 = -(points*sumzx2-sumx2*sumz)/denom
c
c
      return
      end
c
c
c
      subroutine error1 (nitems,k1,k2,z,x,u)
c
c
c       Purpose:  To compute and print out to disk file the
c                 rms error produced in fitting the ldv data
c                 to the gaussian profiles.
c
c
      real k1,k2,z,x(nitems),u(nitems),uc(200),sum,rmse,uc1,b
      integer points
c
c
```

```
c       1. Compute rms error.
c
      points = nitems
      sum = 0.0
      do 10 i = 1,points
c
        uc(i) = exp(k1-k2*x(i)**2)
        sum = sum + (u(i)-uc(i))**2
c
10    continue
c
c
      write (5,*) k1,points
      uc1 = exp(k1)
      b = sqrt(1/k2)
      rmse = sqrt(sum/(points-1))
c
c       2.  Write the height, number of points, centerline velocity,
c           characteristic jet width, and rms error to the file.
c
      write (4,100) z,points,uc1,b,rmse
100   format (2x,'s= ',f10.5,' points= ',i4,' Um= ',f10.5,' b= ',f10.5,
     c' rmse= ',f10.5)
      write (4,101) k1,k2
101   format (2x,'k1= ',f15.5,' k2= ',f15.5)
c
c
c       3.  Write out the actual velocities and computed velocities for
c           comparison.
c
```

```
c
c
      write (4,200)
      do 20 i = 1, points
c
        write (4,201) x(i),u(i),uc(i)
200     format (2x,'Radial coord.,Measured velocity, Computed velocity')
201     format (2x,3f15.5)
c
20    continue
      return
      end
c
c
```

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